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Strategic monitoring informs wilderness management and socioecological benefits

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Abstract

Federally designated wilderness areas in the US are mandated to fulfill social and ecological goals. Long-term monitoring is key to this mandate, yet is seldom consistent across boundaries. Our purpose is to compile literature and data to examine the utility of a strategic forest inventory for meeting wilderness management objectives and for enabling coordinated interagency responses to boundary-crossing challenges (e.g., pollution, wildfires, plant invasions, global changes). We provide examples from a national forest inventory (NFI), which provides nationally consistent information that helps stakeholders comply with protected-areas policy, reduce risks to public safety, define economic opportunities, guide conservation efforts and forecast key ecological processes. For example, the NFI has helped detect long-distance air-pollution, document high-elevation whitebark pine declines and evaluate the risk of wilderness fires spreading to adjacent lands and private property. We identify opportunities to improve monitoring by expanding existing measurements of nonforest ecosystems and linking supplemental monitoring efforts to the existing framework. Though the NFI alone cannot fulfill all monitoring functions, strategic monitoring enables effective wilderness management by revealing socioecological feedbacks between human communities and the wildlands on which they depend.

KEYWORDS

ecological forest management, forest inventory and analysis, knowledge gaps, long-term monitoring, National Forest Inventory, protected status, wilderness character, wilderness stewardship

1 | WILDERNESS CHALLENGES

The purpose of wilderness designation in the United States is to protect areas where human impacts were historically insignificant, to be managed for "recreational, scenic, scientific, educational, conservation and historical use" and enjoyment by people in "such manner as will leave them unimpaired for future use and enjoyment as wilderness" (Wilderness Act, 1964). Federal land managers administering designated wilderness areas in the US face a variety of challenges inherent to protected areas. In an era of accelerating global changes and intercontinental pollution, protection from human impact is not absolute, but rather a matter of degree. Human impacts regularly occur within, or spill over into, protected areas. Impacts include pollution emissions (of air, water, light and noise);

antecedent uses such as livestock grazing and aircraft or motorboat use; permitted uses such as hunting, fishing and stocking of lakes with fish; nonnative species invasions; and fire suppression (Cole & Landres, 1996; Johnson & Agee, 1988). In return, wilderness areas also directly impact adjacent lands and landowners through cross-boundary movement of wildfires, forest diseases, wildlife and non-native plants (Vogeler, Slesak, Fekety, & Falkowski, 2020; White, Harrod, Walker, & Jentsch, 2000). As they recognize the legacy of prior human use, predator control and fire suppression, many wilderness managers have begun to focus on the restoration of ecosystem processes and reintroduction of native species (Johnson & Agee, 1988; van Wagtendonk, 2007). After several decades of wilderness designation and management, we may ask: to what degree are wilderness and conservation goals being met in the face of transboundary challenges? Yet, answering this question requires systematic monitoring that can track changes through time and across different wilderness areas to assess whether management goals are met (Chettri et al., 2015). Our purpose is to describe how strategic monitoring in a national forest inventory (NFI) provides insight into wilderness attributes and management for the provision of socioecological benefits. Specifically, we ask:

1. How can strategic monitoring inform wilderness management?
2. How does strategic monitoring in wilderness inform socioecological benefits?
3. What are ongoing needs for strategic monitoring in wilderness?
4. How to improve strategic monitoring for wilderness stakeholders?

2 | HOW CAN STRATEGIC MONITORING INFORM WILDERNESS MANAGEMENT?

Wilderness managers state that they require science-based information to improve decision-making and serve the public (Dawson, Cordell, Watson, Ghimire, & Green, 2016; Fox & Hahn, 2016). Wilderness areas in the United States are actively managed by four federal agencies, each with a unique approach to management and monitoring. The Bureau of Land Management (BLM), Fish and Wildlife Service (FWS), Forest Service (FS) and National Park Service (NPS) all acknowledge the importance of monitoring and they all agree on broad objectives for maintaining wilderness character (Landres et al., 2015). Yet, the design of monitoring goals and implementation are largely left to individual management units, with most of the work focusing on local ("tactical") issues of importance like social trails in a popular lake basin or the presence of wolverines in a local watershed. Typically, no common design or data management system exists to support interagency coordination (Mealey, 1988). Because ecosystem integrity in a protected area depends on a large surrounding support region (Hansen et al., 2011), information needs do not stop at the protected area boundary. A well-designed sampling and monitoring framework over large spatial and temporal domains can help (Green et al., 2005).

Existing large-scale "strategic" monitoring efforts provide consistency and comparability across wilderness areas and adjacent lands, and enable managers to leverage scarce monitoring resources (Corona, Köhl, & Marchetti, 2003). For example, National Forest Inventories (NFIs) are nationally consistent efforts built from field sampling designed to characterize and monitor vegetation changes and other attributes (Bechtold & Patterson, 2005; Corona et al., 2003). The NFI of the United States, the Forest Inventory and Analysis (FIA) program, produces publicly available data and analyses on structure, composition and change for nearly all forested lands in the country (Gray, Brandeis, Shaw, McWilliams, & Miles, 2012). Similarly, the US Natural Resources Inventory uses a nationally consistent sampling design for vegetation and land-use, with detailed field measurements focused on nonforest cover types like agricultural crops and pasture (Nusser, Breidt, & Fuller, 1998; Nusser & Goebel, 1997). Both efforts account for and describe all land areas in the nation, combining photo-interpretation and alternate data streams to characterize locations by land use and vegetation types not directly measured with field plots. Opportunities to improve integration of these two national surveys exist (e.g., Goebel et al., 1998).

The US NFI program is a standardized, ground-based sampling approach that uses nondestructive measurements combined with remotely sensed and ancillary information to provide sound information on the uses and capacities of US forestlands (Bechtold & Patterson, 2005). Forest inventory design and techniques have matured for over a century to provide robust inference on changes in forest cover and condition (Corona et al., 2003; Köhl, Magnussen, & Marchetti, 2006). While remote sensing technologies may be valuable for assessing vegetation pattern and change across large areas, questions about community composition, vegetation structure and growth and mortality require ground-based measurements. Indeed, NFI field samples are foundational to widely used vegetation models like LANDFIRE (Rollins, 2009), the National Land Cover Database (Homer et al., 2015) and regional vegetation maps used by land managers (e.g., Bell, Gregory, & Ohmann, 2015).

The US NFI sampling frame consists of 2,400-ha hexagons spanning the nation, each containing one randomly selected sample point (Bechtold & Patterson, 2005). Some 12,904 of these sample points fall within the 44.5-million ha designated as wilderness (Figure 1). Accessible, potentially forested sample points are field-visited and measured using nationally standardized field protocols if they meet the "forested" definition (currently or recently ≥10% tree cover and ≥0.4 ha in size). Measurements include tracking individual live and dead standing trees, measuring downed wood and forest floors, quantifying understory vegetation communities, sampling soils, classifying disturbance and damaging agents and measuring site productivity and geomorphic variables. In collaboration with regional managers, further systematic measurements—including at nonforest locations—include vascular plant diversity, lichen communities, fire effects and ungulate browse. These regional enhancements are standardized surveys that comply with the national sampling design. Nonforest plots are measured in wilderness using FIA protocols in the FS

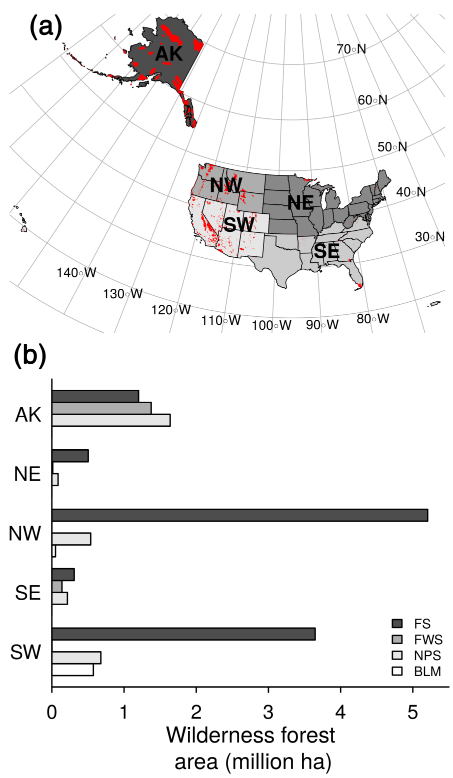

FIGURE 1 Distribution of designated wilderness in the United States. The geographic distribution of designated wilderness (a) is weighted toward the western US and Alaska. Large areas of Alaska wilderness are barren (i.e., ice and rock), and nonforest vegetated is a dominant type for several agencies in Alaska and the Southwest (b). The US Forest Service administers proportionally more forested wilderness land area than other agencies (b). Spatial data are from Wilderness Connect (2021). Area estimates are based on publicly available data from the Forest Inventory and Analysis program (FIA, 2021)

Northern, Pacific Northwest and Pacific Southwest regions, and using NRI protocols on BLM lands. The sheer size and remoteness of interior Alaska mean that its first comprehensive forest inventory is based on measuring one-fifth of the hexagons with estimation bolstered by LiDAR and hyper-spectral imagery (Pattison et al., 2018). More than half of US wilderness (by area) occurs in Alaska (Figure 1b). Analysis of the FIA sample grid indicates 38% of Alaskan wilderness is barren (rock and ice) or water, 44% is vegetated nonforest, and 18% is forest. Outside Alaska, the percentages of wilderness (by area) are 10% barren, 32% vegetated nonforest, and 56% forest, with consistent sampling in most states since at least 2001. Wilderness lands in the United States are administered by NPS, FS, FWS, and BLM. FS administers proportionally more forested wilderness than other agencies. Nationally consistent measurements can help all agencies coordinate monitoring of wilderness attributes to address a wealth of socioecological needs. To address our second question (*how does strategic monitoring in wilderness inform socioecological benefits for wilderness stakeholders?*), we compiled literature examples and summarized original forest inventory data (Table 1) grouped by five socioecological themes.

3 | SOCIOECOLOGICAL THEME 1: MANAGEMENT AND POLICY COMPLIANCE

Interagency wilderness management often focuses on trends in "wilderness character," which includes both biophysical and social components (Landres et al., 2015). NFI measurements of biophysical attributes can help assess the "untramelled," "natural," and "other features" aspects of wilderness character identified in Landres et al. (2015) by assessing spatial and temporal trends in the distribution of forest seral stages, community composition and habitat structure (Table 1). This can inform whether observed conditions are consistent with historical ranges of variability prior to modern human modification, or expected ranges of variation given global changes. In addition, fine-scale species-specific studies based on NFI vegetation data in and around wilderness areas can help assess population viability of plants and animals of concern under the Endangered Species Act (Chojnacky & Dick, 2000; Davis, Dugger, Mohoric, Evers, & Aney, 2011; Zielinski & Gray, 2018). Resource assessments based on NFI data help managers comply with planning requirements (e.g., the National Forest Management Act), including considering whether proposed new wilderness areas would increase inclusion of uncommon ecosystems (Belote, Dietz, & Aplet, 2015).

TABLE 1 Utility of a National Forest Inventory for monitoring wilderness areas, grouped by six socioecological themes

Theme	Example wilderness application	NFI data collected or applied
Management and policy compliance	1. To identify outstanding recreational opportunities for solitude 2. To identify and anticipate changes in culturally important features 3. To meet wilderness management and stewardship objectives for seral stage and unmodified disturbance regimes 4. To guide potential inclusion of future wilderness areas based on uncommon ecosystems 5. To provide citizens consistent information for *all* forested lands	1. Distance from road, site accessibility status, site condition 2. Medicinal and food plants, old-growth groves, wildlife habitat 3. Status and trends of forest conditions, stand age/physical structure, structural complexity 4. Vegetation composition and stand structure, topography 5. Status and trends of forest conditions based on multiple attributes: Vegetation structure, composition and abundance; soils; fuels; downed woody debris; carbon
Public safety and risk management	1. To guide proactive planning of fire suppression or fire use, given risk to adjacent areas 2. To refine access maps and hazard maps for forest worker safety	1. Vegetation structure and fuels quantity/ characterization 2. Geospatial modeling from aerial photo stratification and extensive ground truth
Economic applications	1. To evaluate habitat availability and quality for game animals and non-timber forest products on which local economies depend 2. To reduce uncertainty in carbon accounting and carbon markets 3. To estimate potential economic costs of wildfire, pests, pathogens, and non-native species on adjacent lands and visitation	1. Vegetation abundance, composition and structure 2. Directly measured changes in live and dead carbon pools 3. Disturbance impacts, disturbance agents, invasive plant abundances, food and cultural plant distributions
Conservation applications	1. To estimate threats and suitable habitat for endangered and sensitive species 2. To detect new occurrences of wilderness endemics that would otherwise appear absent 3. To monitor ecosystem impacts of non-native species, pests and pathogens, grazing and air pollution	1. Vegetation composition, structure 2. Trees, understory plants; supplemental invertebrate and wildlife surveys 3. Invasive plants, insect and disease mortality, vegetation decline and grazing impacts, lichen community compositions as bioindicators
Monitoring and forecasting ecological processes	1. To provide relatively unmodified reference conditions for assessing management impacts on other lands 2. To establish historical range of variability for disturbances and ecosystem processes 3. To monitor and forecast biological effects of changes in climate and disturbance regimes	1. Plant succession, tree growth and mortality 2. Disturbance severity and rates 3. Natural regeneration, changes in growth, changes in climate bioindicators

Note: Each theme has several example applications, each matched with publicly available NFI data from the US Forest Service's Forest Inventory and Analysis program.

Currently, the regional percentage of land area designated as wilderness is 15.7% for AK, 0.3% for NE, 5.9% for NW, 0.5% for SE, 6.7% for SW and 4.9% for the nation overall (Wilderness Connect, 2021; Figure 1). In the western US, montane conifer forests (e.g., dominated by *Tsuga mertensiana*, *Picea engelmanii*, *Abies lasiocarpa*) are better represented in wilderness compared to nonwilderness, while dry conifer forests (e.g., dominated by *Pinus ponderosa*, *Pinus monophylla*, *Juniperus* spp.) are not as well represented (Figure 2a,b). Knowing the distribution of vegetation types could help with strategic expansion efforts (Belote et al., 2015) and potentially improve on "gap analysis" efforts based on coarse-scale spatial data or expert knowledge (e.g., Aycrigg et al., 2016; Scott et al., 1993).

4 | SOCIOECOLOGICAL THEME 2: PUBLIC SAFETY AND RISK MANAGEMENT

Wilderness monitoring can illuminate public safety issues related to wildland fires and other disturbances (Table 1). Risks to human well-being and the growing cost of wildfires are drawing attention to the conditions that

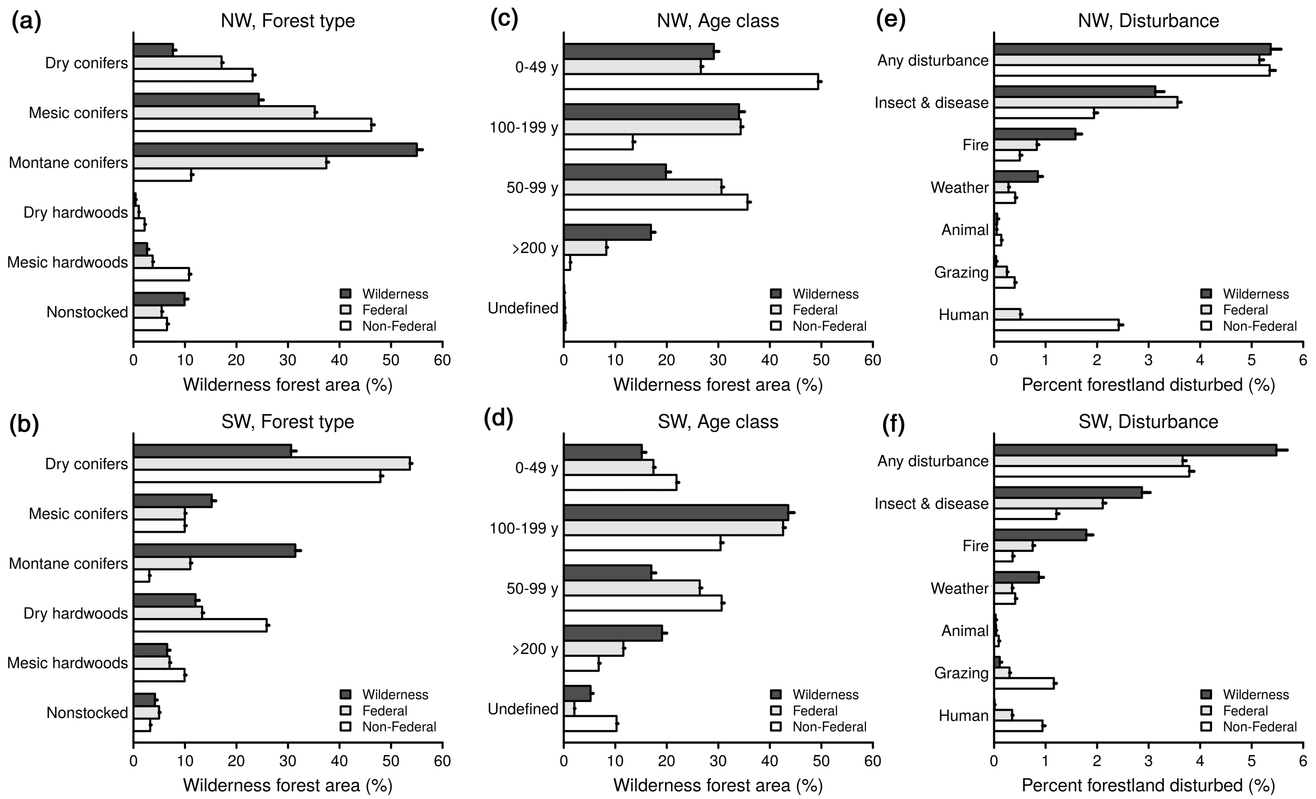

FIGURE 2 Wilderness inventories consistently estimate key forest attributes. Attributes for three ownership types in the US Pacific Northwest (NW) and Southwest (SW; map, Figure 1a) reveal that wilderness areas have distinctive attributes relative to non-wilderness forest lands. In comparison to non-wilderness (federal and non-federal), wilderness areas tended to over-represent montane conifer forests and under-represent dry conifer and hardwood forests (a,b). Relative to non-wilderness, forested wilderness had roughly twice the proportional area in the oldest age class (>200 y) as other non-wilderness federal lands (c, d). Natural disturbance rates (including fire) were commonly higher in wilderness relative to other lands (e, f). Bars = means, whiskers = standard errors. Estimates based on publicly-available data from the US Forest Service's Forest Inventory and Analysis program (FIA, 2021). "NW" and "SW" Regions follow Figure 1

determine fire behavior. A century of fire suppression in most western states has affected dry vegetation types in wilderness areas through direct suppression and prevention of fire spread from adjacent areas (Haugo et al., 2019; Johnson & Agee, 1988). While some agencies actively manage wildfires and may prescribe fire in wilderness, others suppress most fire starts (North et al., 2015). NFI data on living and dead vegetation structure help to quantify fuel loads and wildland fire risks (e.g., LANDFIRE, Rollins, 2009), and are needed to parameterize models that assess the risk of wilderness fires spreading to adjacent public or private lands under different weather scenarios (Barnett, Miller, & Venn, 2016; Scott, Helmbrecht, Parks, & Miller, 2012). Opportunities exist for better use of current data and for collecting additional data to improve knowledge of fire behavior. For example, targeted post-fire measurements of NFI permanent plots can improve modeling of fire-severity predictions (Barker, Fried, & Gray, 2019), and expanded sampling of nonforest locations would extend inference to other habitats. Characterizing fuels and predicting fire behavior are therefore central not only to protecting life and property, but also to preserving cultural and economic resources.

5 | SOCIOECOLOGICAL THEME 3: ECONOMIC APPLICATIONS

Wilderness areas provide a wealth of economic benefits, from direct monetary impacts on adjacent communities, to indirect benefits such as ecosystem services, biodiversity conservation and passive-use (existence) values (Table 1). For example, wilderness visitors and rural development near US wilderness areas account for thousands of jobs in guiding, lodging and subsidiary services resulting in revenues exceeding $700 million USD annually (Hjerpe, Holmes, & White, 2017). Livelihoods in wilderness-adjacent communities often center on hunting and fishing, either by paid recreational guiding or subsistence hunting. NFI monitoring benefits hunting livelihoods by assessing habitat availability and quality for economically important game animals such as elk or moose (Boyce et al., 2003). Surveys that include non-timber forest products can quantify source populations for economically and culturally important plants like ginseng (*Panax quinquefolius*; Chamberlain, Prisley, & McGuffin, 2013). More broadly, NFI measurements in wilderness are important to global economies based on carbon markets; for example, tracking forest carbon for greenhouse gas reduction in the US can yield revenues exceeding $250 billion USD annually (Ramseur & Leggett, 2019). National and regional accounting of forest carbon stocks and fluxes relies heavily on NFI data (Domke, Woodall, Smith, Westfall, & McRoberts, 2012; Gray & Whittier, 2014; Ramseur & Leggett, 2019). Therefore, tracking trends in wilderness disturbances and forest health has ramifications not only for wilderness-adjacent economies (e.g., Davis, Moseley, Nielsen-Pincus, & Jakes, 2014) but also for economies nowhere near a wilderness boundary.

6 | SOCIOECOLOGICAL THEME 4: CONSERVATION APPLICATIONS

Wilderness designation implies obvious conservation benefits, but knowing whether conservation objectives are truly met requires standardized baseline and trend data (Table 1). The NFI can help identify imminent threats and suitable habitat for threatened, endangered and sensitive species that tend to occur in wilderness. A prime example is whitebark pine (*Pinus albicaulis*), a long-lived tree and keystone species which occurs in high-elevation areas and is susceptible to introduced pathogens and climate-driven insect outbreaks (Logan, Macfarlane, & Willcox, 2010) resulting in dramatic population losses across its range (Goeking & Izlar, 2018). Sampling of invertebrates and other key taxa tied to the survey can detect previously unknown occurrences of wilderness-endemic species in biodiversity assessments (e.g., Sikes et al., 2017). Characterizing plant species and vegetation structure can contribute to understanding habitat requirements for rare or endangered wildlife that may migrate across wilderness boundaries. For example, wildlife-harboring old forests, particularly those greater than 200 years of age, are proportionally more abundant in wilderness than on other federal lands and other ownerships (Figure 2c,d). Across large regions, NFI surveys have also successfully identified trends in wilderness air pollution and air quality based on epiphytic lichens' responses to atmospheric nutrient deposition (Jovan, 2008). Detection and attribution of air pollution can inform mitigation efforts that prevent deterioration of wilderness character.

7 | SOCIOECOLOGICAL THEME 5: MONITORING AND FORECASTING BASIC PROCESSES

A fundamental role of wilderness areas is to provide relatively unmodified reference conditions (Wilderness Act, 1964). NFI monitoring can fulfill the goal of baseline measurements, not only to assess specific management impacts, but more broadly to help establish historical ranges of variability for disturbance regimes and other ecosystem-scale processes (Keane, Hessburg, Landres, & Swanson, 2009; van Wagtendonk, 2007). Current NFI inventory data indicate that forest disturbance rates in wilderness areas of the US Southwest and Northwest are at least as great as on non-wilderness lands (Figure 2e,f). Relative to non-wilderness lands, wilderness areas experience greater disturbance impacts from fire, weather and insects and diseases, but lesser impacts from humans and grazing (Figure 2e,f). Inventory-based forecasting can suggest how species regeneration, growth and mortality may change future forest compositions (Monleon & Lintz, 2015; Zhu, Woodall, & Clark, 2012). Other potential uses of a wilderness inventory include the ability to monitor and forecast the biological effects of changing climate and disturbance regimes, especially in parts of the country like Alaska that have extensive areas of both designated and de facto wilderness (Barrett & Gray, 2011). Sampling in these locations could be complemented by student and citizen science initiatives that monitor climate change impacts for the USFS "Chief's 10 Year Wilderness Challenge" (Pitt & Schultz, 2018). The NFI is no substitute for tactical monitoring of specific local processes (e.g., invasive plant expansion in a given wilderness), but NFI data can provide timely information about the frequency and extent of processes occurring at regional scales (Table 1).

8 | WHAT ARE ONGOING NEEDS FOR STRATEGIC MONITORING IN WILDERNESS?

Most strategic monitoring plans attempt to reduce the problem of nonresponse, which for the NFI consists of survey locations that are not accessed due to difficulty navigating to the plot, or by hazardous conditions (e.g., cliffs, rivers) at the plot location (FIA, 2021, and FIA crew records). Safety policies (https://www.fs.usda.gov/pnw/page/pnw-fia-data-collection-safety) describe hazardous conditions under which plot sampling or navigation would pose a clear and present danger to human well-being. Crews expend considerable effort to measure wilderness plots, often requiring several days of travel on

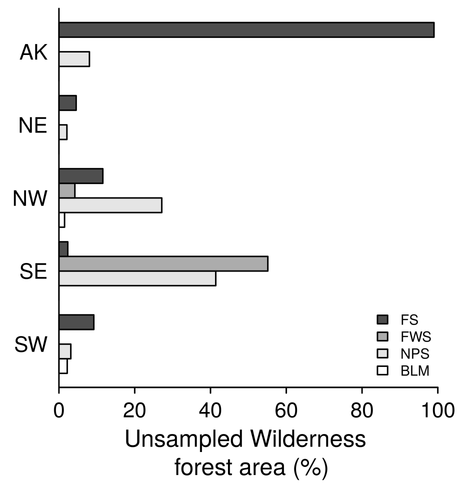

FIGURE 3 Substantial areas of wilderness are not currently sampled. High rates of nonsampled forested wilderness exist in the US Southeast and Alaska because of difficulty accessing plots (FIA, 2021). Regions follow Figure 1

foot, horseback or watercraft to measure a single location (Brown, 2015). Based on the FIA database (FIA, 2021), the percentage of measured, forested wilderness plots >8 km from a road was 93% in Alaska, and 38, 37, and 41% in the montane west ecoregions of Sierra Nevada, North Cascades, and Olympics, respectively. One-way travel times are available for west coast plots, and are >8 hr for 20% of the sampled wilderness plots in these three ecoregions, while it is 0% for Alaska (where most access is by helicopter) and 17% overall for forested wilderness in California, Oregon, and Washington (FIA, 2021, and FIA crew records). By region, the percentage of measured, forested wilderness plots >8 km from a road were NE = 34%, NW = 56%, SE = 3%, and SW = 21%. While nonsampled plots tend to be further from roads than sampled plots, the data to quantify that are not available. Based on the FIA database (FIA, 2021), we calculated nonsampled rates for wilderness by dividing the area weights of nonsampled plots by the sum of forested and nonsampled area weights. In the Southeast, dense mangroves and swamps contributed to high rates of nonsampled forest wilderness on FWS and NPS lands (respectively 55% and 41%, Figure 3). Rugged mountainous terrain and dense vegetation >5 km from trails leads to high rates of nonsampled forest on NPS in the Pacific Northwest (27%) and FS in coastal Alaska (100%) (FIA, 2021). Inventory sampling in Alaska is almost entirely dependent on helicopters to get crews close to plot locations (Barrett & Gray, 2011; Cahoon, Kuegler, & Christensen, 2020). Some wilderness managers include monitoring as one of several administrative duties where judicious use of mechanized equipment is permitted, and enable FIA crews to reach otherwise inaccessible plots by helicopter, though other managers take a different view of appropriate mechanized access (e.g., USDA Forest Service Alaska Region, 2008). Although most Alaska wilderness areas allow fixed-wing aircraft as an antecedent use, the distribution of potential landing sites (lakes, glaciers, sand bars) are not within 5 km of most plots. FIA post-stratification accounts for nonsampled locations by assigning greater weights to sampled plots found in the same stratum as nonsampled ones. While this may be reasonable when nonsampled rates are low, estimation bias may prevail when nonsampled rates are high and/or geographically clumped. For example, lack of NFI data in coastal Alaska wilderness was identified as constraining the conservation assessment of declining Alaska yellow-cedar (*Chamaecyparis nootkatensis*; Bidlack et al., 2017).

9 | HOW TO IMPROVE STRATEGIC MONITORING FOR WILDERNESS STAKEHOLDERS?

Many people view wilderness as "untrammeled" and free from human modification, yet wilderness boundaries are permeable, with frequent exchanges between human communities and natural lands. Without objective and standardized monitoring across wilderness and other lands, we are less able to understand those exchanges and the drivers of change in wilderness landscapes. NRI and FIA inventories provide a consistent foundation for broad-scale assessments on forested and nonforest lands. With publicly available data, analysis tools and customer service, NFI technologies are available to address many pertinent questions (https://www.fia.fs.fed.us/tools-data/index.php).

Opportunities to enhance wilderness monitoring programs exist. First, enhancing access to currently unmeasured areas could remedy sampling gaps that inhibit basic estimation and forecasting. This would fill in "blank" unsampled areas which currently offer managers zero information. Second, expanding measurements to include more nonforest locations would strengthen the basis for understanding ecosystem changes in wilderness areas dominated by desert, alpine or tundra habitats. Third, complementary surveys (e.g., plant diversity, wildlife, invertebrates, soils, climate) at existing sample points can increase the utility of all datasets while minimizing research footprints (Canterbury, Martin, Petit, Petit, & Bradford, 2000). While strategic vegetation inventories cannot answer all wilderness monitoring questions, they continue to inform our understanding of the complex feedbacks between human communities and forested ecosystems. This understanding is ever more relevant as unprecedented changes in climate and disturbance regimes continue to impact wilderness areas and the well-being of the communities that depend on them.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to conceptualization, analysis, interpretation, writing and manuscript review.

DATA AVAILABILITY STATEMENT

All data are publicly available from the US Forest Service's Forest Inventory and Analysis program at: https://www.fia.fs.fed.us/tools-data/index.php.

ETHICS STATEMENT

The article complies with all ethical considerations.

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REFERENCES

Aycrigg, J. L., Tricker, J., Belote, R. T., Dietz, M. S., Duarte, L., & Aplet, G. H. (2016). The next 50 years: Opportunities for diversifying the ecological representation of the National Wilderness Preservation System within the contiguous United States. *Journal of Forestry*, *114*, 396–404.

Barker, J. S., Fried, J. S., & Gray, A. N. (2019). Evaluating model predictions of fire induced tree mortality using wildfire-affected forest inventory measurements. *Forests*, *10*, 958.

Barnett, K., Miller, C., & Venn, T. J. (2016). Using risk analysis to reveal opportunities for the management of unplanned ignitions in wilderness. *Journal of Forestry*, *114*, 610–618.

Barrett, T. M., & Gray, A. N. (2011). Potential of a national monitoring program for forests to assess change in high-latitude ecosystems. *Biological Conservation*, *144*, 1285–1294.

Bechtold, W. A., & Patterson, P. L. (2005). *The Enhanced Forest Inventory and Analysis Program – National Sampling Design and Estimation Procedures. Gen. Tech. Rep. SRS-80*. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Bell, D. M., Gregory, M. J., & Ohmann, J. L. (2015). Imputed forest structure uncertainty varies across elevational and longitudinal gradients in the western Cascade Mountains, Oregon, USA. *Forest Ecology and Management*, *358*, 154–164.

Belote, R. T., Dietz, M. S., & Aplet, G. H. (2015). Allocating untreated "controls" in the National Wilderness Preservation System as a climate adaptation strategy: A case study from the Flathead National Forest, Montana. *Northwest Science*, *89*, 239–254.

Bidlack, A., Bisbing, S., Buma, B., D'Amore, D., Hennon, P., Heutte, T., … Oakes, L. (2017). Alternative interpretation and scale-based context for "No evidence of recent (1995–2013) decrease of yellow-cedar in Alaska" (Barrett and Pattison 2017). *Canadian Journal of Forest Research*, *47*, 1145–1151.

Boyce, M. S., Mao, J. S., Merrill, E. H., Fortin, D., Turner, M. G., Fryxell, J., & Turchin, P. (2003). Scale and heterogeneity in habitat selection by elk in Yellowstone National Park. *Écoscience*, *10*, 421–431.

Brown, M. J. (2015). Estimating mangrove in Florida: trials monitoring rare ecosystems. In S. M. Stanton & G. A. Christensen (Eds.), *Pushing boundaries: new directions in inventory techniques and applications: Forest Inventory and Analysis (FIA) symposium 2015* (pp. 303–309). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Cahoon, S. M. P., Kuegler, O., & Christensen, G. A. (2020). *Coastal Alaska's forest resources, 2004–2013: Ten-year Forest Inventory and Analysis report. Gen. Tech. Rep. PNW-GTR-979*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Canterbury, G. E., Martin, T. E., Petit, D. R., Petit, L. J., & Bradford, D. F. (2000). Bird communities and habitat as ecological indicators of forest condition in regional monitoring. *Conservation Biology*, *14*, 544–558.

Chamberlain, J. L., Prisley, S., & McGuffin, M. (2013). Understanding the relationships between American ginseng harvest and hardwood forests inventory and timber harvest to improve co-management of the forests of eastern United States. *Journal of Sustainable Forestry*, *32*, 605–624.

Chettri, N., Bubb, P., Kotru, R., Rawat, G., Rucha, G., Murthy, M., … Sharma, E. (2015). Long-term environmental and socioecological monitoring in transboundary landscapes: An interdisciplinary implementation framework. In *ICIMOD working paper 2015/2*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.

Chojnacky, D. C., & Dick, J. L. (2000). Evaluating FIA forest inventory data for monitoring Mexican spotted owl habitat: Gila National Forest example. *Western Journal of Applied Forestry*, *15*, 195–199.

Cole, D. N., & Landres, P. B. (1996). Threats to wilderness ecosystems: Impacts and research needs. *Ecological Applications*, *6*, 168–184.

Corona, P., Köhl, M., & Marchetti, M. (Eds.). (2003). *Advances in forest inventory for sustainable forest management and biodiversity monitoring*. Netherlands: Springer.

Davis, E. J., Moseley, C., Nielsen-Pincus, M., & Jakes, P. J. (2014). The community economic impacts of large wildfires: A case study from Trinity County, California. *Society & Natural Resources*, *27*, 983–993.

Davis, R. J., Dugger, K. M., Mohoric, S., Evers, L., & Aney, W. C. (2011). *Northwest Forest Plan—the first 15 years (1994–2008): status and trends of northern spotted owl populations and habitats. Gen. Tech. Rep. PNW-GTR-850*. Portland, OR: U.S.

Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Dawson, C. P., Cordell, K., Watson, A. E., Ghimire, R., & Green, G. T. (2016). The US wilderness managers survey: Charting a path for the future. *Journal of Forestry*, *114*, 298–304.

Domke, G. M., Woodall, C. W., Smith, J. E., Westfall, J. A., & McRoberts, R. E. (2012). Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. *Forest Ecology and Management*, *270*, 108–116.

Forest Inventory and Analysis Database [FIA]. (2021). US Department of Agriculture, Forest Service, Northern Research Station. Retrieved from http://apps.fs.fed.us/fiadb-downloads/datamart.html

Fox, S. A., & Hahn, B. A. (2016). Science informs stewardship: Committing to a national wilderness science agenda. *Journal of Forestry*, *114*, 305–310.

Goebel, J. J., Schreuder, H. T., House, C. C., Geissler, P. H., Olsen, A. R., & Williams, W. R. (1998). *A study on integrating surveys of terrestrial natural resources: the Oregon demonstration project*. Corvallis, OR: U.S. Environmental Protection Agency EPA/600/R-98/032 52. Retrieved from https://ir.library.oregonstate.edu/concern/defaults/c247dx07g

Goeking, S. A., & Izlar, D. K. (2018). *Pinus albicaulis* Engelm. (whitebark pine) in mixed-species stands throughout its U.S. range: Broad-scale indicators of extent and recent decline. *Forests*, *9*, 131.

Gray, A. N., Brandeis, T. J., Shaw, J. D., McWilliams, W. H., & Miles, P. (2012). Forest Inventory and Analysis database of The United States of America (FIA). *Biodiversity & Ecology*, *4*, 225–231.

Gray, A. N., & Whittier, T. R. (2014). Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth. *Forest Ecology and Management*, *328*, 167–178.

Green, R. E., Balmford, A., Crane, P. R., Mace, G. M., Reynolds, J. D., & Turner, R. K. (2005). A framework for improved monitoring of biodiversity: Responses to the world summit on sustainable development. *Conservation Biology*, *19*, 56–65.

Hansen, A. J., Davis, C. R., Piekielek, N., Gross, J., Theobald, D. M., Goetz, S. J., … DeFries, R. (2011). Delineating the ecosystems containing protected areas for monitoring and management. *Bioscience*, *61*, 363–373.

Haugo, R. D., Kellogg, B. S., Cansler, C. A., Kolden, C. A., Kemp, K. B., Robertson, J. C., … Restaino, C. M. (2019). The missing fire: Quantifying human exclusion of wildfire in Pacific Northwest forests, USA. *Ecosphere*, *10*, e02702.

Hjerpe, E., Holmes, T., & White, E. (2017). National and community market contributions of wilderness. *Society & Natural Resources*, *30*, 265–280.

Homer, C., Dewitz, J., Yang, L., Jin, S., Danielson, P., Coulston, J., … Megown, K. (2015). Completion of the 2011 National Land Cover Database for the conterminous United States: Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, *81*, 345–354.

Johnson, D. R., & Agee, J. K. (1988). Introduction to ecosystem management. In J. K. Agee & D. R. Johnson (Eds.), *Ecosystem management for parks and wilderness* (pp. 3–14). Seattle, WA: University of Washington Press.

Jovan, S. (2008). *Lichen bioindication of biodiversity, air quality, and climate: Baseline results from monitoring in Washington, Oregon, and California. Gen. Tech. Rep. PNW-GTR-737 PNW-GTR-737*. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Keane, R. E., Hessburg, P. F., Landres, P. B., & Swanson, F. J. (2009). The use of historical range and variability (HRV) in landscape management. *Forest Ecology and Management*, *258*, 1025–1037.

Köhl, M., Magnussen, S. S., & Marchetti, M. (2006). *Sampling methods, remote sensing and GIS multiresource forest inventory*. Berlin Heidelberg: Springer-Verlag.

Landres, P., Barns, C., Boutcher, S., Devine, T., Dratch, P., Lindholm, A., … Simpson, E. (2015). *Keeping it wild 2: An updated interagency strategy to monitor trends in wilderness character across the national wilderness preservation system. Gen. Tech. Rep. RMRS-GTR-340*. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Logan, J. A., Macfarlane, W. W., & Willcox, L. (2010). Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone ecosystem. *Ecological Applications*, *20*, 895–902.

Mealey, S. P. (1988). U.S. Forest Service wilderness management: Challenge and opportunity. In J. K. Agee & D. R. Johnson (Eds.), *Ecosystem management for parks and wilderness* (pp. 193–215). Seattle, WA: University of Washington Press.

Monleon, V. J., & Lintz, H. E. (2015). Evidence of tree species' range shifts in a complex landscape. *PLoS ONE*, *10*, e0118069.

North, M. P., Stephens, S. L., Collins, B. M., Agee, J. K., Aplet, G., Franklin, J. F., & Fulé, P. Z. (2015). Reform forest fire management. *Science*, *349*, 1280–1281.

Nusser, S. M., Breidt, E. J., & Fuller, W. A. (1998). Design and estimation for investigating the dynamics of natural resources. *Ecological Applications*, *8*, 234–245.

Nusser, S. M., & Goebel, J. J. (1997). The National Resources Inventory: A long-term multi-resource monitoring programme. *Environmental and Ecological Statistics*, *4*, 181–204.

Pattison, R., Andersen, H.-E., Gray, A., Schulz, B., Smith, R. J., & Jovan, S. (2018). *Forests of the Tanana Valley State Forest and Tetlin National Wildlife Refuge, Alaska: Results of the 2014 Pilot Inventory. Gen. Tech. Rep. PNW-GTR-967*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Pitt, A. N., & Schultz, C. A. (2018). Youth-based citizen science monitoring: Case studies from three national forests. *Journal of Forestry*, *116*, 109–116.

Ramseur, J. L., & Leggett, J. A. (2019). *Attaching a price to greenhouse gas emissions with a carbon tax or emissions fee: Considerations and potential impacts*. Washington, DC: Congressional Research Service.

Rollins, M. G. (2009). LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire*, *18*, 235–249.

Scott, J. H., Helmbrecht, D. J., Parks, S. A., & Miller, C. (2012). Quantifying the threat of unsuppressed wildfires reaching the adjacent wildland-urban interface on the Bridger-Teton National Forest, Wyoming, USA. *Fire Ecology*, *8*, 125–142.

Scott, J. M., Davis, F., Csuti, B., Noss, R., Butterfield, B., Groves, C., … Wright, R.G. (1993). Gap analysis: A geographic approach to protection of biological diversity. *Wildlife Monographs*, *123*, 3–41.

Sikes, D. S., Bowser, M., Morton, J. M., Bickford, C., Meierotto, S., & Hildebrandt, K. (2017). Building a DNA barcode library of Alaska's non-marine arthropods. *Genome*, *60*, 248–259.

USDA Forest Service Alaska Region. (2008). *Helicopter access to conduct Forest Inventory and Analysis (FIA) in wilderness: Record of decision (ROD)*. Alaska Region, Juneau, AK: USDA Forest Service.

van Wagtendonk, J. W. (2007). The history and evolution of wildland fire use. *Fire Ecology*, *3*, 3–17.

Vogeler, J., Slesak, R., Fekety, P., & Falkowski, M. (2020). Characterizing over four decades of forest disturbance in Minnesota, USA. *Forests*, *11*, 362.

White, P. S., Harrod, J., Walker, J. L., & Jentsch, A. (2000). Disturbance, scale, and boundary in wilderness management. In *Proceedings RMRS-P-15, volume 2* (pp. 27–42). Ogden, Utah: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Wilderness Act. (1964). Public Law 88-577 (16 U.S.C. 1131-1136).

Wilderness Connect. (2021). University of Montana, Missoula, MT. Retrieved from https://wilderness.net/

Zhu, K., Woodall, C. W., & Clark, J. S. (2012). Failure to migrate: Lack of tree range expansion in response to climate change. *Global Change Biology*, *18*, 1042–1052.

Zielinski, W. J., & Gray, A. N. (2018). Using routinely collected regional forest inventory data to conclude that resting habitat for the fisher (*Pekania pennanti*) in California is stable over ~20 years. *Forest Ecology and Management*, *499*, 899–908.

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