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Climate Change Vulnerability Assessment for Forest Management: The Case of the U.S. Forest Service

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Abstract: Forest managers need access to targeted scientific information about the impacts of climate change in order to adapt to climate change. Vulnerability assessments address this need and are common across a range of disciplines and geographies; however, the practice of vulnerability assessment has revealed challenges that warrant further examination in a specific context. The U.S. Forest Service, a national forest-management agency in charge of 78 million hectares, has developed a collection of climate change vulnerability assessments to support adaptation by forest managers. We conducted a qualitative document analysis, informed by a series of research interviews with scientists, of 44 vulnerability assessments developed for the U.S. Forest Service. We found that partnerships between research scientists and land managers were central to the development of vulnerability assessments in the U.S. Forest Service. Assessment processes vary across settings. As the practice has developed, vulnerability assessments increasingly cover larger spatial extents and a broader range of resources associated with forest management. We identified ways in which vulnerability assessments can support decision-making, including approaches already in use and opportunities to improve practice. In particular, we discuss how vulnerability assessments are well-positioned to support the development of land-management plans, which set strategic management direction for periods of at least a decade. This paper provides baseline knowledge on a fundamental aspect of a large national forestry agency's climate change adaptation strategy, with many findings transferable to the study of other forest-management organizations.

Keywords: climate change adaptation; vulnerability assessment; U.S. Forest Service; science–management partnerships

1. Introduction

In order to support climate change adaptation planning, forest managers need access to targeted scientific information in order to devise appropriate management actions, identify priority resources and locations for intervention, and inform decision-making [1,2]. Climate change vulnerability assessments help natural-resource managers address these needs. Here, we use “vulnerability assessments” to describe the processes and resulting documents that identify the potential impacts of climate change to forests and associated resources in particular locations [3,4]. Policies highlight vulnerability assessments as central elements to adaptation, yet questions remain regarding the extent to which contemporary vulnerability assessment practices achieve their goals, and how principles for vulnerability research, a field that incorporates insights from a range of locations and research disciplines, apply to particular operational contexts, especially ones where government forestry agencies play central roles [5].

The management of national forests in the United States offers a useful context to examine these extant questions pertaining to vulnerability research. In the U.S. Forest Service, a federal land-management agency in charge of 78 million hectares (193 million acres) of forest and grasslands

located throughout the United States, scientists and managers are working together to coproduce vulnerability assessments, a central element of the agency's adaptation strategy [2,6,7]. Over the past decade, they have completed a collection of vulnerability assessments that cover nearly the entire National Forest System. In this paper, we analyze the state of the practice, with the intents of understanding this element of the agency's climate change adaptation strategy, supporting the future application and development of vulnerability assessments by forest-management agencies, and addressing key questions in vulnerability research. Our account provides baseline knowledge on vulnerability assessments, a foundational piece of the U.S. Forest Service's climate change adaptation strategy. Our findings facilitate future research on this agency's adaptation efforts, support scientists engaging in research that directly supports management, and offer opportunities for subsequent research that contrasts forest adaptation in the United States with activities in other countries.

1.1. Climate Change Vulnerability Assessments: Basics and Outstanding Questions

A variety of fields, including engineering and psychology, use the concept of vulnerability. However, scholars have established approaches specific to examining impacts of climate change on ecosystems, other biophysical topics, and social–ecological systems [8,9]. In this context, vulnerability includes three components: exposure, sensitivity, and adaptive capacity. The Intergovernmental Panel on Climate Change (IPCC), published in 2007, suggested analyzing vulnerability across these three components [10]. Exposure describes “the degree of stress on a system”. Sensitivity refers to “the degree to which a resource will be affected by that stress”. Adaptive capacity describes “the ability of a resource to accommodate or cope with potential climate change impacts with minimal disruption” [11] (p. 23). Subsequent IPCC reports, including the synthesis published in 2014, separate exposure from vulnerability and use a conceptual framework that treats vulnerability, hazards, and exposure as components of risk [12]. This demonstrates the evolving nature of understandings of vulnerability and of how best to summarize the impacts of climate change in order to support adaptation. In line with this evolution, scholars have identified several points of contention about vulnerability research that inform our research questions and that are interesting to explore in the context of forest management by government agencies [5]. We discuss these in the remainder of this section.

Scientists who are trained in analyzing the impacts of climate change often take the lead in producing vulnerability assessments; however, scholars also advocate for the involvement of stakeholders in vulnerability research [8,13]. Without involving stakeholders, vulnerability researchers run the risk of problematically classifying populations and locations as vulnerable without understanding what causes this vulnerability [5]. Furthermore, adaptation activities happen through social processes that reflect stakeholders' preferences and existing policies [9]. To overcome this challenge, vulnerability assessments can integrate top-down scientific methods with bottom-up involvement of stakeholders, including environmental managers and their constituents [13,14]. Previous research described how a lack of appropriate information limits U.S. federal land managers' ability to adapt to climate change and suggested that improved networks between managers and scientists could alleviate this challenge [15,16]. Partnerships between scientists and managers have emerged as a central element of the U.S. Forest Service's response to climate change [2,7]. Accordingly, in our analysis, we considered the actors involved and processes used to develop vulnerability assessments.

A variety of social and biophysical disciplines have contributed scientific knowledge to the development of vulnerability assessment practices [3]. Vulnerability assessment offers a common framework for examining climate change impacts to a range of different endpoints, including human communities, ecosystems, or their combination, social–ecological systems [4,8,11]. However, the assessment of vulnerability for different endpoints requires different disciplinary methods, which may vary in their sophistication and relevance to managers. Vulnerability research has faced challenges in terms of integrating different disciplines, especially in terms of balancing the relative contributions of social and biophysical factors in determining vulnerability [5]. By law, the U.S. Forest Service

manages, for a range of uses, national forest land and ecosystem services, thus requiring the agency to implement adaptation across several natural-resource management disciplines [17]. Accordingly, we considered the different types of resources considered in the agency's vulnerability assessments, in order to understand how vulnerability assessment processes address different scientific disciplines.

Though a global phenomenon, climate change has localized effects, and vulnerability assessments must consider the impacts of climate change across different spatial extents [9,18]. However, scale issues have proved difficult to address in vulnerability assessments [5]. Past studies have demonstrated that scientific information on the impacts of climate change is often presented at spatial resolutions that are not useful for managers, leading to a barrier to adaptation; however, downscaling projected climate change impacts to resolutions relevant to managers is also challenging and introduces uncertainty [19,20]. These types of scalar mismatches are particularly applicable in forest management [21,22]. In addition to considering the scope of assessments in terms of the types of social and ecological endpoints and resources covered, we also considered scope in terms of the spatial-scale levels addressed in vulnerability assessments.

The concept of vulnerability can have a vague meaning, and multiple approaches to conceptualizing vulnerability exist [5]. Approaches to determining vulnerability may involve expert elicitation processes and group deliberation, synthesis of peer-reviewed literature, climate change projections and modeling, geospatial analyses, or detailed case studies [3,4,11,13]. These methods present conclusions about vulnerability in different ways, with some comparing the relative vulnerabilities of different species, others identifying watersheds that are especially vulnerable, and still others presenting narrative summaries of how climate change may affect a particular resource. All of these types of approaches are in use in the Forest Service, and it was necessary to consider this variety in order to get a sense of the current state of practice [4,11].

Scholars and practitioners often criticize vulnerability research for a lack of application in actual decision-making processes [5,23]. According to some authors, overcoming these criticisms requires a more robust recognition of governance and policy dynamics in the development of assessments [23,24]. Others argue for the inclusion of stakeholders and decision-makers in the development of assessments, as these actors can provide insight on the policy constraints and opportunities for climate change adaptation that they face [7,13,25]. Ideally, vulnerability assessments provide support for managers making decisions about an inherently uncertain future [26]. Improving the application of assessments in forest-management decisions represents a current priority for the Forest Service [2,27]. Accordingly, we considered ways in which assessments support decision-making, including through discussions of uncertainty.

1.2. An Overview of Climate Change Adaptation Policy and Practice in the U.S. Forest Service

Here, we provide context on the U.S. Forest Service's climate change adaptation strategy, in order to illustrate how vulnerability assessments fit into this government agency's approach to adaptation. A series of executive orders from the Obama presidential administration established climate change adaptation and mitigation as policy priorities across the federal government; federal agencies, including the U.S. Forest Service, developed strategic agency-specific policies in response [28,29]. The Forest Service established the Climate Change Performance Scorecard in 2010, which required national forests and other management units to assess their progress in addressing climate change. It described objectives for each management unit with regard to climate change, and units scored themselves based on ten "yes/no" questions. One question asked, "Does the Unit actively engage with scientists and scientific organizations to improve its ability to respond to climate change?" Another question asked, "Has the Unit engaged in developing relevant information about the vulnerability of key resources, such as human communities and ecosystem elements, to the impacts of climate change?" This policy thus directed management units to engage in science-management partnerships and develop vulnerability assessments [30]. In line with the scorecard, Forest Service research scientists developed frameworks for

adaptation that emphasize vulnerability assessments [4,11]. Some vulnerability assessment processes had begun prior to the establishment of the scorecard [7].

Vulnerability assessments inform land management planning on national forests, a process where interdisciplinary teams determine the trajectory of management activities for periods upwards of a decade. The 2012 planning rule (36 CFR §219 et seq.), which outlines land management planning requirements in line with the National Forest Management Act of 1976, dictates that plans “maintain or restore the ecological integrity of terrestrial and aquatic ecosystems and watersheds”, while considering climate change as a system stressor (36 C.F.R. §219.8). The rule lays out a three-phase planning approach, including assessment of available information, plan development, and monitoring; stressors, like climate change, must be addressed during all three phases. It also requires forest plans to use “best-available scientific information” to inform the development of plans (36 C.F.R. §219.3). While one alternative proposed during the analysis leading to the 2012 planning rule would have required vulnerability assessments as a step in the planning process, the final planning rule does not provide specific legal requirements for vulnerability assessments [31]. Nonetheless, in line with the general requirements to consider climate change in planning, one intention of vulnerability assessments has been to support the plan-revision processes conducted under this rule [4]. In addition to plan revision, the authors of vulnerability assessments intend for the documents to support climate change considerations throughout other aspects of forest management, including the planning and execution of management projects [2].

1.3. Summary and Research Questions

The overall goal of our research was to ascertain the current state of vulnerability assessment practice in a government forestry agency. Our specific research questions are as follows and are based on the literature and early stages of our research (described in the next section): (1) Who participates in the development of vulnerability assessments and what processes do they use? (2) What are the scopes of vulnerability assessments? (3) How do assessments define and analyze vulnerability? (4) How do assessments support application in decision-making? Our work advances a growing body of literature focused on understanding vulnerability to climate change in different contexts and the challenges that scientists and practitioners face when working with this concept (e.g., see [5]). Furthermore, we believe that our findings are useful to practitioners using vulnerability assessments in management and scientists seeking to develop assessments in other contexts.

2. Materials and Methods

The goal of our research was to address several key questions in vulnerability research through qualitative research on vulnerability assessment practices in the U.S. Forest Service. Our primary research method for this paper was a qualitative analysis of vulnerability assessment documents, a process that we designed based on a series of initial key informant interviews. We worked closely with the Forest Service’s Office of Sustainability and Climate, which oversees adaptation in the agency and funded this work, to identify topics of interest and inform our approach. We retained control over the design of our research and how we present our findings.

We began our research by conducting interviews with 11 scientists who had worked on vulnerability assessments, in order to get a sense of what to look for in our document analysis. In semi-structured interviews, we asked scientists a series of questions about the processes that they used to develop assessments and topics that we should consider in our analysis of existing assessments [32,33]. In line with a protocol approved by our university’s Institutional Review Board, we recorded and transcribed these interviews. We then coded the transcripts of the interviews; coding refers to a process of assigning short, descriptive phrases to blocks of text in order to identify themes [34]. The intent of this analysis was to identify general themes and specific areas of inquiry for our document analysis. We settled on four themes that were commonly discussed by participants and that reflect themes in the literature: processes and partnerships used; scale and resources covered by documents; approaches to

defining and assessing vulnerability; and application of assessments. These themes align with our research questions, and the literature on vulnerability research indicates that these topics warrant further research.

Based on the interviews and other background research, we developed a document coding guide to analyze vulnerability assessment documents, and solicited feedback on the guide from interview participants. This guide included criteria for documents organized across the themes described above (see Appendix B for interview guide). For example, within the theme of scale and resources, we recorded quantitative and qualitative information about the spatial area covered by assessments, as well as the general categories and specific species of plants and animals addressed in the assessments. We used a spreadsheet to collect information for the criteria. For each vulnerability assessment, we began by skimming the document to get a general sense of its scope and structure; then, we conducted a targeted read of the document that was focused on specific topics of interest. For certain criteria, we used specific keyword searches to identify pertinent information; for example, searching for the term “define” and its derivatives (e.g., “definition”) helped to efficiently identify definitions of vulnerability and other key terms. In addition, for other questions, we focused on specific sections of documents; for example, we first looked at document introductions to understand who participated in the vulnerability assessment process. Our focus on documents is a useful research approach since these products can influence policy decisions [35]. We then composed analytic memos to summarize findings across our different research themes [34]. In order to ensure the validity of our findings, we sought to triangulate our findings across sources [33,34]. In addition to reporting findings in this paper, we are using this initial document analysis to inform case study research investigating the implementation of vulnerability assessments. We identified vulnerability assessments, starting with a list provided by the Forest Service and did additional searches to identify additional assessments. We aimed to sample all assessments published during this period that intended to inform national forest management. Our scope of analysis includes both assessments that were peer-reviewed and ones published without undergoing peer review.

3. Results

In total, we reviewed 44 vulnerability assessments developed between 2010 and 2018 (see Appendix B for more details). These assessments cover national forests located across all nine regions of the National Forest System. These assessments collectively include vulnerability determinations for forest types, key plant and wildlife species associated with forests, ecologically important endpoints like disturbance regimes and stream temperatures, hydrology, human uses, and ecosystem services. As discussed above, our analysis proceeds along four primary questions (see Section 1.3), which reflect key themes in the literature on vulnerability research.

3.1. Participation, Partnerships, and Processes

In general, assessment processes involved several steps, including convening a partnership of managers and scientists, assessing the current status of the system, projecting future climatic conditions, discussing future vulnerabilities, and identifying potential management responses [2]. Several common approaches existed, which varied in use across the National Forest System regions. Table 1 characterizes different approaches across regions, and Table 2 provides more details on processes used, including those described below. Two approaches were most common. First, the Adaptation Partners group developed assessments for several groups of forests in the Pacific Northwest (Region 6 of the National Forest System) and conducted regional-scale assessments for the Northern (Region 1) and Intermountain (Region 4) Regions [36–38]. Their approach involved scientists working with their disciplinary counterparts in management to research and write chapters focused on a range of different resources. Second, using the Climate Change Response Framework (CCRF) developed by the Northern Institute of Applied Climate Science, scientists and managers have developed a series of bioregional assessments in the Midwest and Northeast (Region 9) [11]. While these CCRF assessments

cover national forests, they are intended for a broader audience of forest managers from a range of jurisdictions. In addition to these two approaches, another common approach applies criteria (generally seven different metrics), which were originally developed by the Manomet Center, a conservation organization, and the Northeast Association of Fish and Wildlife Agencies, to assess vulnerability [39]. This approach has been used to assess vulnerability in California, the Rocky Mountain Region, and for several national forests in the Intermountain Region [40–42]. Other assessments relied on general literature review and synthesis [43]. A few assessments used methodologies specific to unique types of endpoints, including watersheds and socioeconomic endpoints [44,45]. Collectively, these processes for vulnerability assessment reflect a range of methodological approaches and reflect discretion available to decision-makers in different regions and management units and partner scientists to determine an appropriate approach for vulnerability assessment.

Table 1. Summary of vulnerability assessment approaches by U.S. National Forest System region.

Region	Assessment Approach
1: Northern	Region-wide, multi-resource assessment
<i>Details:</i> All management units are covered by the regional Northern Rockies Adaptation Partnership assessment that was completed in 2018. The assessment covers a range of resources, including vegetation, snowpack and water, fish and wildlife, ecological disturbance, recreation, ecosystem services, and cultural resources. In addition, several assessments have been conducted for individual forests in the region, including a socioeconomic assessment for the Nez Perce–Clearwater National Forest and a watershed assessment for the Lolo National Forest.	
2: Rocky Mountain	Region-wide assessments for ecosystems and infrastructure
<i>Details:</i> Published in 2018 as a General Technical Report, a region-wide assessment covers six priority ecosystem types, including glaciated valleys, spruce–fir, and Ponderosa pine. Units in the region also have access to a region-wide assessment of infrastructure published in 2016. Other assessments focused on single units include two collaborative assessments covering the Gunnison Valley and the San Juan National Forest and a literature synthesis assessment intended to support forest plan revision on the Shoshone National Forest.	
3: Southwestern	Several region-wide assessments covering different topics
<i>Details:</i> Several region-wide assessments cover Region 3, including one that summarizes general climate trends, one that summarizes the literature on ecological impacts, and an unpublished effort projecting potential vegetation change. In addition, Forest Service staff published in 2018 a General Technical Report analyzing socioeconomic vulnerability in the region, which builds on some of these previous assessments.	
4: Intermountain	Region-wide, multi-resource assessment
<i>Details:</i> All management units are covered by the regional Intermountain Adaptation Partnership assessment completed between 2015 and 2018. The assessment covers a range of resources, including vegetation, hydrology and water, fish and wildlife, ecological disturbance, recreation, ecosystem services, and cultural resources. In addition, researchers have written assessments for aquatic resources and aspen, using the NEAFWA approach for the Uintah–Wasatch–Cache and Ashley National Forests in Utah.	
5: Pacific Southwest	Multiple subregional ecosystem assessments; regional assessment for recreation and infrastructure
<i>Details:</i> Using the NEAFWA approach, the nongovernmental organization EcoAdapt completed several ecosystem assessments for several subregions in California (e.g., national forests in the Sierra Nevada). The Adaptation Partners group has also begun a vulnerability assessment of recreation and infrastructure for the national forests in the Sierra Nevada.	
6: Pacific Northwest	Multiple subregional, multi-resource assessments
<i>Details:</i> Beginning in 2008, the Adaptation Partners group has completed a series of multi-resource assessments focused on one or more contiguous national forests and national parks. These focus on subregions, such as the Olympic Peninsula of Washington and the Blue Mountains of Oregon. Authors of these assessments include researchers, NFS managers, and other partners. These assessments cover nearly all units in the region, aside from the Siuslaw National Forest. Scientists have also published a region-wide vulnerability assessment of tree species that considers their vulnerability based on their genetics.	
8: Southern ¹	Region-wide briefing papers based on the literature review tool TACCIMO; intended to cover forests under other ownerships
<i>Details:</i> The USDA Southeast Regional Climate Hub published a vulnerability assessment in 2015 that covers the entire region. Several other fact sheets have been developed in the region intended to support private landowners. This reflects the fact that much of the forestland in this region is owned and managed by private landowners. The TACCIMO ² tool, developed in this region, provides an additional tool for managers to identify relevant peer-reviewed literature on climate change vulnerabilities, and it has been used as the basis for a literature synthesis vulnerability assessment for the El Yunque National Forest.	

Table 1. Cont.

Region	Assessment Approach
9: Eastern	Multiple subregional ecosystem assessments; intended to cover forests under other ownerships
<i>Details:</i> The CCRF group has developed a series of assessments focused on bioregions throughout the Midwest and Northeast, which cover the national forests in this region. Given the prevalence of forests managed by nonfederal entities in this region, these assessments intend to support adaptation in nonfederal ownership contexts, as well. Based on our analysis, the Midewin National Tallgrass Prairie, located in this region, is the only management unit in the National Forest System without access to a vulnerability assessment of some sort.	
10: Alaska	Individual assessments for each of the two national forests in the region
<i>Details:</i> This region includes only two individual national forest units. In 2014, EcoAdapt developed an assessment of aquatic resources on the Tongass National Forest. In 2017, USFS scientists published a vulnerability assessment for the Chugach National Forest.	
¹ In 1965, the U.S. Forest Service eliminated Region 7, incorporating units from it into Regions 8 and 9; ² TACCIMO stands for Template for Assessing Climate Change Impacts and Management Options.	

Table 2. Common types of vulnerability assessment approaches in use by the U.S. Forest Service.

Approach	Scale	Target Resources	Example(s)
Adaptation Partners	Several units or NFS region	Vegetation/ecosystems; disturbances; hydrology (including snowpack); fish and wildlife; recreation; ecosystem services; cultural resources	Northern Region Adaptation Partnership
<i>Details on approach:</i> These assessments summarize the “state of the science” on the impacts of climate change for resources. These assessments generally use modeling of the impacts of climate change, including for vegetation types and hydrologic systems, identify vulnerable geographic areas, and synthesize peer-reviewed literature. Managers and scientists work together to write chapters of these assessments.			
Climate Change Response Framework	Bioregion	Vegetation/ecosystems	New and England and Northern New York Ecosystem Vulnerability Assessment
<i>Details on approach:</i> This approach uses climate projections, literature review, and vegetation models as the basis for expert elicitation processes, where managers and scientists familiar with the bioregion of interest rate the vulnerability of forest types in terms of the potential impact of climate change and an ecosystem’s adaptive capacity. Groups use these individual vulnerability ratings to then determine consensus vulnerability ratings for forest types.			
Northeastern Association of Fish and Wildlife Agencies and Manomet Center	Several or individual national forest(s)	Vegetation/ecosystems; wildlife habitat; hydrology and watersheds	Rocky Mountain Region Aquatic and Terrestrial Ecosystems Vulnerability Assessment
<i>Details on approach:</i> This approach uses expert elicitation processes to rate the vulnerability of a resource on a 5- or 7-point scale based on a series of criteria, which generally include the following: capacity for range shifts; vulnerability of cold-adapted, foundation, or keystone species; sensitivity to extreme climatic events; intrinsic adaptive capacity; dependence on a specific hydrologic regime; potential for climate change to exacerbate effects of non-climate stressors; and likelihood of managing or alleviating climate change effects.			
Watershed vulnerability assessment	National forest; analyzed by watershed	Watersheds and associated values (e.g., infrastructure and fish)	Lolo National Forest Watershed Vulnerability Assessment
<i>Details on approach:</i> These assessments use geospatial models of projected changes in temperature and precipitation, as well as the sensitivity of watersheds, to determine the comparative vulnerabilities of watersheds found within a national forest. These assessments allow managers to prioritize specific watersheds based on their relative vulnerabilities to climate change. Chapters on watersheds and hydrology in Adaptation Partnership assessments have also employed this approach.			
Literature synthesis	National forest	Vegetation/ecosystems; hydrology; fish and wildlife; recreation; ecosystem services; cultural resources	Climate Change on the Shoshone National Forest
<i>Details on approach:</i> This approach, generally conducted for forest plan revision, involves synthesizing information in peer-reviewed literature about climate change impacts.			
Socioeconomic assessments	National forest or NFS region	Ecosystem services (e.g., grazing, forest products, water, and recreation)	Socioeconomic Vulnerability to Ecological Changes to National Forests and Grasslands in the Southwest
<i>Details on approach:</i> These assessments consider how ecological change as a result of climate change affects ecosystem services and regional economies. In addition, these assessments consider socioeconomic and demographic characteristics that may make communities proximate to national forests vulnerable.			

Most assessments reflected input from science–management partnerships, where scientists and managers collaborated to identify target resources, interpret climate change projections and data, and

make determinations about the vulnerability of resources. However, a few assessment processes only involved participation from scientists. While assessment publications did not consistently report numbers of participants, many assessments brought together between 20 and 30 participants. At the high end, the regional assessments for the Northern and Intermountain Regions each engaged over 250 individuals through a series of workshops. Scientists involved in these partnerships generally worked for the U.S. Forest Service's Research and Development branch; however, some scientists worked for nongovernmental conservation organizations and universities. Managers involved in most assessments worked for the Forest Service, including at the regional level or on national forests. Some of these managers had previous graduate-level scientific training and shared authorship of assessment chapters with scientists. CCRF assessments also involved managers working for state, local, and tribal government management agencies, consultants and managers for private land, and conservation organizations.

3.2. *Scope of Assessments: Spatial Scale and Target Resources*

We use the term “scope of assessments” to describe the spatial scale and target resources or endpoints addressed in assessments. Spatial extents of assessments range from around 28,000 acres (11,000 hectares) for the El Yunque National Forest to 30 million acres (12 million hectares) of NFS lands covered by the Intermountain regional assessment. Several of the CCRF assessments cover bioregions of up to approximately 50 million acres (20 million hectares) across multiple different ownerships. Many of the assessments focus on extents between 2 million and 10 million acres (0.8–4 million hectares) across one or several national forests. Collectively, the assessments considered in this assessment cover nearly the entire National Forest System; more information on CCVAs considered in this analysis is provided in Appendix A. Some units are covered by multiple different assessments, including a regional assessment, as well as an assessment specific to that unit. Regional assessments often subdivide their areas into subregions and also report key findings for individual management units.

Assessments cover target resources or endpoints that reflect the different uses, resources, and management priorities included in the Forest Service's mission. Most commonly, assessments addressed the vulnerability of ecosystem, forest, or vegetation types; however, assessments conceptualized this type of endpoint in different ways. Assessments also covered non-forested ecosystem types, including aquatic ecosystems, rangeland vegetation, and special habitat types. For many assessments, input from managers in science–management partnerships helped to determine the ecosystem types of interest. Other common endpoints included fish, wildlife, and plant species; recreational activities; ecosystem services and human uses; watersheds, hydrology, and associated values; and infrastructure. Some assessments incorporated climate change impacts on disturbance processes, such as fire, into determinations of vulnerability of vegetation types [36], whereas others provided separate chapters that assess the vulnerability of disturbance regimes [37]. Some assessments linked biophysical vulnerabilities to impacts on human communities. The IAP, for example, examined this linkage in terms of the vulnerability of different ecosystem services, including water systems. An assessment for the Southwestern Region analyzed socioeconomic vulnerability in terms of the potential for vegetation change as a metric for exposure, economic ties between communities and national forestlands to describe sensitivity, and indicators of social adaptive capacity [44].

3.3. *Defining and Assessing Vulnerability*

We examined how assessments define and conceptualize vulnerability, finding that these approaches generally reflected guidance from agency scientists. Assessments commonly used the following definition for vulnerability from the IPCC's 2007 report: “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes” [10] (p. 6). Most assessments discussed vulnerability in terms of its components of exposure, sensitivity, and adaptive capacity. Exposure and sensitivity were often combined into the single metric of potential impact. One scientist that we interviewed reflected on this approach and

challenges associated with assessing adaptive capacity, saying the following: “Often, the vulnerability assessments [follow] the 2007 IPCC report . . . that broke vulnerability into those three aspects: exposure, sensitivity, and adaptive capacity . . . I think we’ve done a pretty good job on the first two, [but adaptive capacity] is harder to get at”. This challenge manifested in how some assessments include management interventions, such as planting a particular species of tree, as an element of adaptive capacity, while others focused only on factors intrinsic to that resource, such as a tree species’ ability to regenerate, to describe adaptive capacity.

Assessments generally included projections of future temperature and precipitation under climate change scenarios, and researchers used these projections as inputs for the determination of vulnerability through modeling, group deliberation, or expert judgments. Commonly projected climate endpoints in vulnerability assessments included the following: increases in mean annual temperature; percentage changes in precipitation; seasonal minimum, mean, and maximum temperature and precipitation; and snowpack metrics, including snow-water equivalent and snowmelt dates. Projecting climate change involves a series of methodological decisions, including identifying general circulation models (GCMs) to represent physical climate dynamics and selecting forecasts of greenhouse gas emissions scenarios, which project flows of emissions into the atmosphere. Assessments tended to report ensemble projections, which average across different GCMs, and ranges that correspond to low-end and high-end emissions projections, to capture inherent uncertainties about the future trajectory of climate change. Newer assessments used Representative Concentration Pathways from the latest iteration of the Coupled Model Intercomparison Project (CMIP5) to anticipate levels of greenhouse gases in the atmosphere; in addition, these assessments drew on summaries of GCMs provided by the CMIP5. Assessments generally reported on projected climate endpoints aggregated over two or three future time periods, using 30-year time slices (e.g., 2030–2059 and “2040s”), which are considered large enough to account for annual variability. Many assessments included end-of-century projections, and some included the caveat that forest planning timeframes cover only the next 10–20 years, highlighting a disconnect between projection timeframes and planning time horizons. Some assessments supplemented projections of future climate with summaries of historical climate for the 20th century, which offered readers the opportunity to contextualize past events and trends in terms of climate.

Assessments presented determinations of vulnerability as narrative descriptions, rankings, categorizations, and the identification of vulnerable spatial areas. Narrative summaries qualitatively described vulnerability across its subcomponents based on the review of peer-reviewed literature and modeling results. Most assessments included maps and tables summarizing model results to supplement these narrative descriptions. Facilitated group deliberation processes provide venues for the determination of vulnerability ratings organized in categories (e.g., low-medium-high). In these processes, each participant rated vulnerability in terms of subcomponents (e.g., potential impact and adaptive capacity) or criteria (e.g., range shift capacity and dependence on a specific hydrologic regime). These scores were averaged to provide an overall determination. Watershed assessments used downscaled climate projections and hydrologic modeling outputs to develop exposure and sensitivity indices presented on a map for each watershed within a national forest. Many assessments provided accounts of the level of uncertainty associated with determinations of vulnerability. Presentations of uncertainty often differentiated between a lack of or limited availability of scientific information and conflicts in evidence as sources of uncertainty.

3.4. Support for Application in Decision-Making

Our analysis revealed several ways in which vulnerability assessments intended to support application in management decision-making. First, many assessments were peer-reviewed before publication. Most of these assessments (29 of 44) were published by the Forest Service’s research stations as General Technical Reports, through a process that involves peer review. In addition, scientists have published papers in refereed journals, summarizing vulnerability assessment processes [1,2,46,47].

Some assessments were published without peer review as white papers released by either national forests or partner organizations. Vulnerability assessment publications included devices to support the use of assessments, including one-page summaries, summary tables, and textboxes. Maps of model outputs also supported managers in identifying specific areas that were especially vulnerable. In addition, assessment processes used ESRI Storymaps to provide underlying spatial data to managers. Interview participants noted that partnerships create collective ownership of the end-product, build trust of scientists amongst managers, and promote mutual education. One scientist described the mutual learning that results from these arrangements: “I think that’s been very informative for both sides, because the scientists have some things to learn as well.”

In developing assessments, authors intended to support improved decision-making in land management. As assessment documents and interviews with scientists highlight, many assessments were developed specifically to support upcoming forest-plan revisions in the focal regions [43,48]. Forest-plan revisions are a key venue for setting management direction for periods of a decade or more. The assessments that we reviewed sought to support planning by providing information on the current and future status of social and ecological conditions that could inform the development of plan content and by identifying management strategies that have adaptation benefits. Vulnerability assessments also sought to inform the motivation, design, and analysis of management projects through processes dictated by the National Environmental Policy Act. However, some scientists noted that they have to avoid providing recommendations on specific policy decisions, particularly when land managers working in jurisdictions other than the National Forest System may want to use the assessments. Accordingly, assessments tended to focus on “climate-smart” management principles that offer broad advice or processes for incorporating climate change into project planning without specific prescriptions. For example, many assessments emphasized that managers seek to restore and maintain resilient ecosystems.

A key element of assessments were workshops where authors used presentations of preliminary assessment results to elicit discussion about actions that managers could take in response to identified vulnerabilities. These adaptation actions were included in tables in the published vulnerability assessments, thus providing a resource for managers seeking to identify management responses to climate change. Many of these actions were things that managers were already doing absent considerations of climate change, and, so, application may come through recognizing how existing management approaches prove to be “climate-smart”. The Adaptation Partners group has compiled adaptation activities identified through several different vulnerability assessment processes into the Climate Change Adaptation Library of the Western United States (<http://adaptationpartners.org/library.php>). This compendium of adaptation strategies provides a starting point for managers not initially involved in vulnerability assessments to learn about potential responses to climate vulnerabilities [1].

4. Discussion

Vulnerability assessments offer a practical tool to support adaptation across a range of environmental management contexts. As our study demonstrates, these processes require that scientists and managers take the theoretical concept of vulnerability—one with global reach—and determine how it applies to management practices in specific contexts. Understanding this process requires research that examines vulnerability assessment in a specific organizational setting, as we do in this paper. Our analysis focuses on the current state of practice of vulnerability assessment in the U.S. Forest Service, a large national forest-management agency with a purview that spans a wide range of ecological and social contexts. Here, we discuss how our findings contribute to the literature on vulnerability and support improved adaptation practices in forest and land management, both in the United States and elsewhere. The remainder of this section is organized in four subsections, each corresponding to one of our research questions. These sections summarize findings in terms of the literature and raise questions for adaptation practice and future research.

4.1. Science–Management Partnerships: Similarities and Variations

The literature suggests that the people involved in a vulnerability assessment will shape analytic decisions in developing the assessment, as well as its prospects of being applied [5,13]. While processes for integrating the collective insights of participants varied, most vulnerability assessments considered in our analysis used science–management partnerships. By design, these partnerships involve the intended end-user, i.e., the land manager, in the development of the product. This is an established best practice in the literature and agency policies [7,13,30]. Our findings highlight some variations in the extent to which assessments involved managers, however, with some processes involving relatively limited engagement of managers beyond workshops to identify priorities and present information. In other processes, scientists and managers shared responsibility for a range of different tasks, including determining relative vulnerabilities through group deliberation, authoring reports, and identifying potential adaptation activities that managers could implement.

While the Forest Service is already using science–management partnerships, several dimensions of these arrangements warrant further attention. First, science–management partnerships should seek to involve line officers, such as district rangers and forest supervisors, in the development of vulnerability assessments, as these individuals in leadership roles ultimately make decisions about a unit's priorities and where to invest its resources. Second, it would be useful to consider the extent to which partnerships are involving managers working at local levels, such as Ranger Districts in the Forest Service, versus primarily involving Regional or National Forest-level staff. These ground-level staff may be able to contribute local knowledge to the process and would have opportunities to implement vulnerability assessments in local decision-making. Managers working in these roles, however, often have limited time and capacity to devote to these efforts, and, if managers perceive involvement in vulnerability assessments as a burden, then the effectiveness of these processes will diminish. Third, while some vulnerability assessment processes considered in this study have involved nongovernmental organizations and other external entities, it is worth considering where stakeholders external to the agency, such as recreationists, ranchers, and water utilities, fit in vulnerability assessment processes. These stakeholders are affected by the impacts of climate change on national forests and may be able to actively support adaptation actions. Accordingly, for science–management partnerships and the vulnerability assessments that they produce to be effective, these efforts need to recognize the ways in which forest management organizations' structural characteristics affect decision-making and work to ensure that the learning that results from participating in a vulnerability assessment reaches the people in positions to be able to make a difference.

Even within the U.S. Forest Service, a single federal agency, a range of vulnerability assessment processes are in use, with differences especially apparent across regions of the National Forest System. This reflects the level of discretion available to decision makers working at different jurisdictional levels of the agency to determine how best to meet general agency directives regarding climate change adaptation. Decisions made through this discretion may reflect managers' individual preferences, their interpretations of how best to achieve objectives, and their understandings of the differences in the ecological and social characteristics of the contexts in which they work. This lack of a uniform set of procedures for vulnerability assessments allows for the tailoring of vulnerability assessments to specific decision-making situations, which, in turn, may support application; however, this may also mean that certain areas lag behind others in terms of their access to robust information to support adaptation, leading to large variations in adaptation success across the agency. Other forest management organizations thus must decide whether they want to establish prescriptive guidelines for vulnerability assessment or provide discretionary space for local managers and scientists to work out site-specific approaches.

4.2. The Expanding Scope of Assessments

The literature has identified challenges in addressing issues of scale in vulnerability research [5,49]. Current scientific projection and modeling methods may be unable to credibly produce information

at the spatial resolution that managers would find useful in decision-making; downscaling climate projections and models of ecological impacts introduces additional uncertainty [5,18,50]. The spatial extents of vulnerability assessments are covered in this study vary. While many of the earlier assessments covered single national forest units, several of the more recent assessments cover broader spatial extents, including entire NFS regions. A smaller-scale assessment may prove more salient to local managers and can include more focused analysis tied to specific places familiar to managers, such as individual watersheds [50]. However, larger-scale assessments, like the regional Intermountain Adaptation Partnership and Northern Rockies Adaptation Partnership assessments, allow for more efficient coverage of management units in terms of effort from scientists, and, by bringing together managers from different management units, broader scale assessments can facilitate learning among managers about practices in other units and coordinated adaptation responses across contiguous units, a key need in addressing the crosscutting impacts of climate change [51]. Furthermore, these assessments focus on broader spatial extents which align with the resolution at which projections and modeled impacts of climate change are produced. Future research should consider whether this type of learning across management units is occurring, how the agency's hierarchical structure that also allows for decentralized decision-making shapes these learning processes, and how scientists can support managers in learning how broad climate trends apply in specific places [52].

A next step for the forest vulnerability assessment is to combine the efficiency of regional assessments with features that increase salience to local land managers. We found that regional assessments are incorporating devices to support salience to local managers, including dividing regions into subregions, providing summaries of results for each management unit, and providing downscaled spatial data and maps when relevant. As the literature suggests, the network of science–management partnerships that has emerged as a result of vulnerability assessments could help to navigate the inherent scalar mismatches between land management, ecological processes, and the impacts of climate change [21,22]. However, future research should examine how managers deal with these scalar challenges in real-world adaptation decision-making processes. Ultimately, this challenge in vulnerability assessments reflects a persistent institutional fit challenge for forest-management organizations, where the scale levels at which forest managers operate often differ from the levels at which ecological processes play out, and, in turn, the scale levels at which scientists operate. In response to this challenge, forest-management organizations need to establish programs focused on brokering knowledge between scientists and managers especially across scalar levels, staffed by individuals that understand local management units and possess the technical skills and broader perspectives necessary to make sense of the science [53]. The U.S. Forest Service regions in the Pacific Northwest and California have existing ecology programs that fulfill this function, but efforts to scale up these programs and expand them beyond these regions would support the further evolution of vulnerability assessment and adaptation in the agency [54].

Vulnerability research spans multiple social and biophysical scientific disciplines [5]. For the Forest Service and other agencies mandated to manage for multiple objectives, it is useful for vulnerability assessments to cover multiple endpoints corresponding to these various objectives, which range from timber production to providing wildlife habitat [55]. As our research shows, the regional-scale assessments for the Intermountain and Northern Regions, especially, capture a wide range of endpoints of interest to managers, including tree species, broad ecosystem types, unique ecosystems, wildlife species, fish habitat, physical resources associated with hydrology, and the links between social systems and ecosystems. By covering a larger spatial scope, these regional assessments may also provide opportunities to efficiently cover more types of resources. It remains to be seen whether methodologies and resulting information from these different disciplines range in their sophistication and whether managers working on specific resources are more likely to engage in the development and application of vulnerability assessments.

4.3. Toward Integrated Vulnerability Determinations

Given the crosscutting nature of climate change, integrative approaches to adaptation prove necessary, and vulnerability assessments can support these efforts by identifying opportunities to align adaptation efforts occurring in different resource areas and to merge social and ecological dimensions of forest vulnerability. Policy scholars argue for integrated efforts across different environmental sectors to take on climate change [56,57]. However, the U.S. Forest Service's administrative structure separates budgets and staff by resource area, which can present a challenge to integrated management approaches [58]. As we note above, approaches to analyzing vulnerability used in the agency vary depending on the resource in question, as well as the management context of interest. Assessment documents tend to present vulnerability determinations in separate sections for different resources. To better support integrative approaches to adaptation, vulnerability assessments could incorporate additional chapters that discuss how vulnerabilities of different resources relate to one another, and managers could consult spatial overlays of vulnerabilities of different resources to prioritize specific locations for adaptation interventions. The U.S. Forest Service's planning rule includes regulatory justification for these approaches, noting that plans should support "integrated resource management" (36 CFR §219.10) defined as "multiple use management that recognizes the interdependence of ecological resources and is based on the need for integrated consideration of ecological, social, and economic factors" (36 CFR §219.19). More broadly, this need for integration highlights how adaptation to climate change increasingly requires collaboration between environmental managers working in different arenas. Applied science approaches, such as vulnerability assessments, can support this interdisciplinary collaboration; however, there is a need to develop approaches to constructively merge insights from multiple disciplines in a way that proves useful to natural-resource managers.

A lack of integration between social and ecological factors has presented a challenge to vulnerability research [5,21]. To address the social–ecological linkages inherent in vulnerability, the literature suggests techniques including "bottom-up" qualitative case studies, top-down quantitative indicators, and participatory scenario processes [14,59,60]. Furthermore, the concept of ecosystem services, by design, recognizes the benefits that ecosystems provide human communities [4]. Several of the assessments that we examined address these linkages, including through qualitative case studies [61], "top-down" indicators of socioeconomic vulnerability [44], and chapters addressing ecosystem services [37]. There exist opportunities to scale up this focus on social and ecological linkages in vulnerability assessments and adaptation practices, in line with requirements of the 2012 planning rule. In addition to emphasizing environmental sustainability, the rule indicates that plans should contribute to "social and economic sustainability" (36 CFR §219.8). Similarly, ecosystem services are included in the planning rule (36 CFR §219.8 and §219.10). A focus on social–ecological linkages and key ecosystem services could offer a useful starting point for managers working out what adaptation actions to prioritize. Accordingly, there is a need for more robust methods for forecasting impacts of climate change on key ecosystem services that extend beyond the qualitative description of impacts to ecosystem services that are currently prominent in the vulnerability assessments that we reviewed.

4.4. Supporting Application

A common criticism of vulnerability research is a lack of relevance to policy-driven decision-making [5,23]. Vulnerability assessments represent an interim output in the chain of scientific and policy outputs that occurs as part of adaptation processes in forest governance. Accordingly, for assessments to serve their intended purpose, these documents will need to inform subsequent policy decisions, and these policy decisions will need to have ecological and social outcomes that manifest in forests that are better adapted to climate change. Here, we consider ways in which vulnerability assessments can link to specific decisions required by policy in the context of the agency that is the focus of our study. For the Forest Service, plan revision processes represent an important opportunity for implementing adaptation based on vulnerability assessments [28]. Furthermore, the 2012 planning rule represents one of the most significant changes in several decades to the policy processes employed

by the U.S. Forest Service, and the plans that national forests will produce under this rule will guide management activities for periods upwards of a decade [62]. Our findings demonstrate that many assessments were intentionally developed to support plan revision. In other forest management contexts, it is likely that strategic planning situations where managers consider larger landscapes and longer timeframes would also be important venues for the application of vulnerability research.

As we have discussed above, there exist opportunities to align vulnerability assessments with specific planning requirements, which would enhance their applicability in decision-making. For example, the planning rule requires that plans provide for ecosystem integrity, which is defined as “the quality or condition of an ecosystem when its dominant ecological characteristics . . . occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence” (36 CFR §219.19). Vulnerability assessments can provide useful information on what the “dominant ecological characteristics” of a system will be in the future, thus allowing for a comparison with the current conditions and the natural range of variation [63]. For wildlife, assessments offer useful information about whether particular species are likely to continue to occupy a given management unit, which can help forests identify “species of conservation concern”, a required topic in the planning rule (36 CFR §219.9). A key product of vulnerability assessments are suggestions for adaptation activities, which could be incorporated into specific plan components, as several recent forest plans have done. However, it would be useful to investigate the ways in which managers reconcile this information on vulnerability with other expectations that they face in the context of planning. These include ensuring public participation, using the best scientific information available, and providing for multiple uses [64]. Furthermore, an important pursuit for future research involves determining the extent to which policy decisions that incorporate information from vulnerability assessments result in improved adaptation prospects for forests.

Managing for future forests under climate change requires accepting the notions that prediction of the future is inherently uncertain, current knowledge of the impacts of climate change on forests is limited, and disagreements about how to respond exist [26,65–67]. For managers, there are disincentives to acknowledge uncertainty in cases where they perceive conflicts with other legal requirements and planning norms [67]. To counter this, peer-reviewed vulnerability assessments offer managers credible sources to use to understand uncertainty and describe this uncertainty in potentially contentious planning processes. Our analysis of assessments indicates that these documents, as well as the group deliberations that occur as part of assessments, could reduce some types of uncertainty. In particular, vulnerability assessments could help managers identify locations and indicators to prioritize for subsequent monitoring. However, more work is needed to understand how vulnerability assessments support decision-making in light of irreducible uncertainty about the future.

5. Conclusions

Adapting to climate change is a daunting yet important task for contemporary forest managers. Access to scientific knowledge about the impacts of climate change on forests makes this challenge more manageable. Vulnerability assessments and their underlying science–management partnerships, offer a means for managers to understand what science can tell them about managing for a changing and uncertain future, though their decisions about adaptation will ultimately be guided by existing policies in addition to science. Our paper establishes foundational knowledge on vulnerability assessments in one government forest management agency, the U.S. Forest Service. This area of practice is evolving and will remain important as opportunities for the application of vulnerability assessments in adaptation decision-making increasingly present themselves. As a large government agency that manages a vast number of forestlands for multiple different and sometimes competing purposes, the U.S. Forest Service offers a useful case to examine the practice of vulnerability assessments and their prospects for supporting adaptation. While not all of the specific findings in our paper will apply to forest management in other contexts, the overarching themes that we highlight—science-management

partnerships as a venue for learning the scientific and policy dimensions of adaptation, for one—prove instructive across a wide range of forest management contexts.

The current status of vulnerability assessments in the U.S. Forest Service reflects an early adaptation success in that scientists and their partners have developed a collection of assessments that, as a whole, cover the National Forest System, as well as forests under other management jurisdictions. However, more work will be necessary as managers begin to apply assessments in guiding their actions. In their paper summarizing the state of forest adaptation practices in the United States and Canada, Halofsky and coauthors wrote, “We are optimistic that climate change awareness, climate-informed management and planning, and implementation of adaptation in forest ecosystems will continue to evolve in Canada and the US” [2] (p. 95). The literature on climate change and conservation now emphasizes optimism in response to vexing environmental challenges, arguing for a focus on “bright spots” [68] (p. 1) or “small wins” [69] (p. 1). Identifying and sharing successes, as well as approaching the challenge of adaptation with optimism, can help adapters navigate conflict, collaborate, and innovate [68–70]. The networking opportunities and new knowledge that have resulted from vulnerability assessments represent a series of small wins, and broader-scale change may result from these initial small wins if researchers and agency leadership share these successes widely, help managers that are stuck, and provide appropriate resources for managers to overcome barriers.

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Appendix A

This appendix includes a summary of vulnerability assessments considered in this analysis (Table A1).

Table A1. Summary of vulnerability assessments included in this analysis.

Region	Name	Approach	Spatial Extent (Acres)	Spatial Extent Description	Resources	
1	All ¹	Assessing the Vulnerability of Watersheds to Climate Change	Watershed VA	Various national forests	Several national forests	Ecosystems; Aquatic species ² ; Water/hydrology ³ ; Recreation; Infrastructure; Ecosystem services
2	R-1	Northern Rockies Adaptation Partnership	Adaptation Partners	27 million	Region	Ecosystems; Vegetation species; Disturbances; Wildlife; Aquatic species; Water/hydrology; Recreation; Ecosystem services
3	R-1	A CCVA for Resources of Nez Perce–Clearwater National Forests	NEAFWA	4.0 million	National forest	Ecosystems; Vegetation species; Disturbances; Wildlife; Water/hydrology; Recreation; Other ecosystem services

Table A1. Cont.

Region		Name	Approach	Spatial Extent (Acres)	Spatial Extent Description	Resources
4	R-1	Nez Perce–Clearwater NF Forest Plan Assessment: Socioeconomic CCVA	Expert elicitation	4.0 million	National forest	Water/hydrology; Infrastructure; Ecosystem services
5	R-1	Watershed VA: Lolo NF	Watershed VA	3.3 million	National forest	Aquatic species; Water/hydrology
6	R-1	Kootenai Idaho Panhandle Zone Climate Change Report	Literature synthesis	5.4 million	Several national forests	Ecosystems; Vegetation species; Disturbances; Wildlife; Water/hydrology; Recreation; Ecosystem services
7	R-2	CCVA of Aquatic and Terrestrial Ecosystems in the US Forest Service Rocky Mountain Region	NEAFWA	22 million	NFS Region	Ecosystems
8	R-2	San Juan/Tres Rios CCVA	NEAFWA	5 million (1.9 million USFS)	National forest and neighboring public land	Ecosystems
9	R-2	Climate Change on the Shoshone National Forest, Wyoming	Literature synthesis	2.4 million	National forest	Ecosystems; Disturbances; Wildlife; Aquatic species; Water/hydrology; Recreation; Ecosystem services
10	R-2	Regional-Scale CCVA for Infrastructure in the National Forests and Grasslands of the Rocky Mountain Region	Spatial analysis	22 million	NFS Region	Infrastructure
11	R-2	Gunnison Basin CCVA	NEAFWA	2.4 million (1.3 million USFS)	National forest and neighboring public land	Ecosystems; Vegetation species; Wildlife; Ecosystem services
12	R-3	Assessing Climate Change Vulnerability for Ecosystems of the Southwestern US	Literature synthesis	20 million	NFS Region	Ecosystems; Vegetation species; Wildlife; Water/hydrology
13	R-3	Southwestern Region Climate Change Trends and Forest Planning	Literature synthesis	20 million	NFS Region	Ecosystems; Vegetation species; Disturbances; Wildlife; Aquatic species; Water/hydrology; Recreation; Ecosystem services
14	R-3	Socioeconomic Vulnerability to Climate-Related Changes to National Forests in the Southwest	Socio-economic	20 million	NFS Region	Water/hydrology; Recreation; Ecosystem services
15	R-4	Assessment of Watershed Vulnerability to Climate Change for the Uinta-Wasatch-Cache and Ashley National Forests, Utah	NEAFWA	3.6 million acres	Several national forests	Ecosystems; Vegetation species; Wildlife; Disturbances; Water/hydrology
16	R-4	Assessment of Aspen Ecosystem Vulnerability to Climate Change for the Uinta-Wasatch-Cache and Ashley National Forests, Utah	NEAFWA	3.6 million	Several national forests	Ecosystems; Vegetation species

Table A1. Cont.

Region		Name	Approach	Spatial Extent (Acres)	Spatial Extent Description	Resources
17	R-4	Intermountain Adaptation Partnership	Adaptation Partners	34 million	NFS Region	Ecosystems; Vegetation species; Disturbances; Wildlife; Water/hydrology; Recreation; Infrastructure; Ecosystem services
18	R-5	Sierra Nevada Climate Adaptation Project	NEAFWA	12 million	Several national forests	Ecosystems; Disturbances; Wildlife; Recreation; Ecosystem services
19	R-5	Southern California Climate Adaptation Project	NEAFWA	3.7 million	Several national forests	Ecosystems
20	R-5	Northern California Climate Adaptation Project	NEAFWA	6.5 million	Several national forests	Ecosystems
21	R-5	Sierra Nevada Recreation and Infrastructure Vulnerability Assessment	Adaptation Partners	11 million	Several national forests	Infrastructure; Recreation
22	R-6	Blue Mountains Adaptation Partnership (BMAP)	Adaptation Partners	5.3 million	Several national forests	Ecosystems; Aquatic species; Water/hydrology; Infrastructure
23	R-6	North Cascadia Adaptation Partnership (NCAP)	Adaptation Partners	5.9 million	Several national forests and neighboring public land	Ecosystems; Wildlife; Water/hydrology; Infrastructure
24	R-6	South Central Oregon Adaptation Partnership (SCOAP)	Adaptation Partners	5.3 million	Several national forests and neighboring public land	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Recreation; Ecosystem services
25	R-6	Southwest Washington Adaptation Partnership (SWAP)	Adaptation Partners	1.3 million	National forest and neighboring public land	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Infrastructure
26	R-6	Olympic Adaptation Partnership (OAP)	Adaptation Partners	1.6 million	National forest and neighboring public land	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Infrastructure
27	R-6	Southwest Oregon Adaptation Partnership (SWOAP)	Adaptation Partners	2.7 million	National forests and neighboring public land	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Recreation; Ecosystem services
28	R-6	Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP)	Adaptation Partners	2.8 million	Several national forests and neighboring public land	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Infrastructure; Recreation; Ecosystem services
29	R-6	Climate Change and Forest Trees in the Pacific Northwest: A VA and Recommended Actions for National Forests	Species modeling	25 million	NFS Region	Ecosystems; Vegetation species

Table A1. Cont.

	Region	Name	Approach	Spatial Extent (Acres)	Spatial Extent Description	Resources
30	R-8	Southeast Regional Climate Hub CCVA and Adaptation and Mitigation Strategies	Literature synthesis	N/A	General	Ecosystems; Ecosystem services
31	R-8	North Carolina's Emerging Forest Threats: Management Options for Healthy Forests	Literature synthesis	N/A	General	Ecosystems; Vegetation species; Wildlife; Aquatic species; Ecosystem services
32	R-8	Protecting Your Forest Asset: Managing Risks in Changing Times	Literature synthesis	N/A	General	Ecosystems; Disturbances
33	R-8	Climate Change Effects in El Yunque National Forest, Puerto Rico, and the Caribbean region	Literature synthesis	28,000	National forest	Ecosystems; Vegetation species; Disturbances; Wildlife; Aquatic species; Recreation
34	R-9	Central Appalachians Forest Ecosystem VA	CCRF	19 million	Ecoregion	Ecosystems; Vegetation species
35	R-9	Northern Wisconsin and western Upper Michigan Forest Ecosystem VA	CCRF	16 million	Ecoregion	Ecosystems; Vegetation species
36	R-9	Minnesota Forest Ecosystem VA	CCRF	23 million	Ecoregion	Ecosystems; Vegetation species
37	R-9	Michigan Forest Ecosystem VA	CCRF	17 million	Ecoregion	Ecosystems; Vegetation species
38	R-9	Northern Wisconsin Ecosystem VA	CCRF	19 million	Ecoregion	Ecosystems; Vegetation species
39	R-9	Chicago Wilderness Region Urban Forest VA	CCRF	7 million	Ecoregion	Ecosystems; Vegetation species
40	R-9	Central Hardwoods Ecosystem VA	CCRF	42 million	Ecoregion	Ecosystems; Vegetation species
41	R-9	Mid-Atlantic Forest Ecosystem VA	CCRF	60 million	Ecoregion	Ecosystems; Vegetation species
42	R-9	New England and New York Forest Ecosystem VA	CCRF	53 million	Ecoregion	Ecosystems; Vegetation species
43	R-10	A CCVA for Aquatic Resources in the Tongass National Forest	NEAFWA	17 million	National forest	Ecosystems; Aquatic species; Water/hydrology
44	R-10	CCVA for the Chugach National Forest and the Kenai Peninsula	Literature synthesis	7 million	National forest	Ecosystems; Wildlife; Aquatic species; Water/hydrology; Infrastructure; Ecosystem services

Acronyms: CCRF—Climate Change Response Framework; CCVA—Climate Change Vulnerability Assessment; VA—vulnerability assessment. Notes: ¹ includes units in each of the nine NFS regions. ² Aquatic species category includes fish. ³ Water/hydrology category includes assessment of snowpack and storm risks to roads and trails.

Appendix B Interview Guide

- Describe your **involvement in developing** vulnerability assessments.
- What was the **most recent assessment** you worked on? What role did you play?
 - Describe the **process for developing** that assessment.
 - Do you recall **any key moments** in the process?
- Looking back, are you aware of **any mistakes** that you made in past assessments?
- What have you learned about conducting vulnerability assessments over time?

5. Has the process of developing vulnerability assessments **changed your beliefs/ideas** about forest management?
6. Based on this learning, have you **changed your approach** to developing vulnerability assessments?
7. Have you noticed **differences in management contexts** covered by assessments?
 - c. Was there anything surprising to you about the management contexts covered by the assessments?
 - d. How did you change your assessment approach to suit these different contexts?
8. In your impression, **how do managers make management decisions?** What factors to they consider?
9. What do you hope forest managers will get out of vulnerability assessments?
10. Are you aware of **recent management decisions/actions** motivated by the assessments?
11. Do you have any suggestions about how to improve the application of vulnerability assessments?
12. What are **next steps** for vulnerability assessment processes?

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