Wildfire and Forest Management: Opportunities for HCI Research

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Wildfire and forest management increasingly rely on geospatial technologies, i.e., data and tools contributing to the geographic mapping and analysis of the Earth, to inform measures for the control of wildfires. Nevertheless, challenges arising from domain experts adopting these complex, non-intuitive technologies are not well understood. We interviewed 12 participants in wildfire and forest management to explore the technical and socio-technical nature of these challenges, revealing that (1) knowledge and data are fragmented across stakeholders, ranging from governmental agencies to small landowners. This fragmentation causes participants to (2) struggle in sharing knowledge and expertise. Participants (3) voice concerns about model bias since decisions informed by geospatial technologies can have far-reaching impacts. Yet, they (4) face barriers engaging people most impacted by these decisions. We detail an HCI research agenda that includes: exploring opportunities to connect stakeholders and sharing knowledge, standardizing decision-making, and engaging local communities.

CCS Concepts: • **Human-centered computing** → **User studies**; *Usability testing*; • **Social and professional topics** → Governmental regulations; • **Applied computing** → Environmental sciences;

Additional Key Words and Phrases: Sustainability, wildfire and forest management, Geospatial Technologies, Spatial Analysis, Wildfires, Model Bias in Geospatial Systems, Knowledge Fragmentation, Ecological Decision Support Systems, Interdisciplinary Approaches, Local Community Engagement

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1 Introduction: Tilling the Soil

The increasing frequency and intensity of wildfires in the U.S. have been linked to climate change [52]. Forests, some thousands of years old and serving as vital carbon sinks, are being transformed by fires and "megafires" [109, 154]. This transition has profound and significant adverse consequences on biodiversity and ecosystem services that improve human health and well-being [25, 69, 135].

Simultaneously, the use of *geospatial technologies*, i.e., data and tools contributing to the geographic mapping and analysis of the Earth, in wildfire and forest management is surging because they are facilitating efforts to control and mitigate wildfires [6, 66, 115]. Previous HCI research acknowledges that geospatial technologies present unique challenges to their users [74, 132, 164, 177]. However, little is known about the specific challenges in the context of wildfire and forest management. Considering the widespread effects that wildfires pose to ecosystems, we seek to identify the function and challenges of geospatial technologies in this new context.

Many **Sustainable HCI (SHCI)** researchers have critiqued prior investigative efforts in this domain for their limited scope and narrow focus on *tools* in and of themselves, such as persuasive technologies aimed at changing the behaviors of individuals [55]. Instead, these researchers are advocating for technologies to be examined *within the systems* in which they are deployed to enrich understanding of the multifaceted and dynamic challenges of sustainability [28, 111, 140, 141]. At the same time, these system-focused approaches have faced their own criticism for relying on non-interventional studies (e.g., [24, 75, 82]).

In response to these myriad calls, our study aims to analyze both technology *and* the broader socio-technical system that support geospatial technology use [19]. Importantly, responses to issues such as wildfire prevention often occur within complex decision-making processes [26], and a holistic understanding of the dynamics between the social systems and technology is essential to design meaningful interventions. We further contribute an HCI research agenda that identifies opportunities for interventions, additional study, and engagement, with the goal of inspiring actionable research that extends beyond non-interventional approaches, as Bremer et al. [28] suggest.

In particular, we explore the following **Research Questions (RQs)**:

- *RQ1*: What specific challenges emerge in the use of geospatial technologies in wildfire and forest management?
- *RQ2*: How are these challenges shaped by the socio-technical system of wildfire and forest management?
- *RQ3*: What role could HCI play in facilitating the work of domain experts in wildfire and forest management?

To address these questions, we conducted semi-structured interviews with 12 participants working in wildfire and forest management. We find that (1) knowledge and data are fragmented across an immense number of distinct and diverse stakeholders, ranging from governmental decision makers to local community members. This fragmentation leads participants to (2) struggle in sharing knowledge and expertise. Furthermore, participants (3) are concerned about model bias and interpretability because they recognize that decisions informed by geospatial technologies have far-reaching impacts. Yet, participants (4) face barriers communicating with those who might be most impacted, such as local communities and the public. Based on these results, we propose an HCI research agenda exploring future work and opportunities to connect stakeholders and policy-makers, facilitate knowledge sharing, standardize decision-making, communicate CS research approaches and engage local communities.

2 Background and Related Work: The Root of the Problem

Wildfires are becoming increasingly frequent and severe [46]. Effective management of fires involves a variety of land management strategies, which are encompassed by the broader field of forest management, the focus of our study. Wildfire and forest management often rely on geospatial technologies. Although recently there has been a noticeable increase in the adoption of such technologies to effectively manage forests, HCI researchers have yet to fully explore how they are used and applied [6, 66, 177]. We discuss these topics in the following subsections.

2.1 Wildfires Amidst Climate Change

The escalating wildfire crisis in the U.S. is indicative of the effects of climate change. About 4.2 million acres of forests, grassland, and other habitats burned in California alone between 2020 and 2021 [39], with about 116,000 of those acres burning in the Bobcat Fire in Los Angeles County [64, 169]. Though these wildfires predominantly burned wildlands, the 2025 Palisades and Eaton fires in Los Angeles County, on the other hand, were characterized as "the second most destructive" in California's history for their impact on urban areas [88]; they burned 12,000 structures and 40,000 acres of land [32]. Similarly, Oregon recently experienced its most severe fire season on record, with nearly 1.5 million acres burned in 2024 [13].

Though we focus on the North American context, similar concerns are echoed globally. For instance, wildfires in Australia and South Africa, specifically referred to as "bushfires" or "veld fires," respectively, for the type of vegetation burned, also pose severe ecological and societal threats [8, 63, 174]; this article uses the term "wildfire" while acknowledging the global variation in terminology and context. These events evoke a repeating chorus of "unthinkable," "unprecedented," and "unimaginable," setting and breaking records year after year [170].

Beyond forest destruction, the effects of wildfires on humans are profound. Annually, smoke from wildfires globally accounts for 260,000–600,000 deaths [84]. In 2014, the Northwest Territories in Canada experienced a 42% increase in respiratory-related hospital visits amid widespread smoke, significantly affecting residents' physical and emotional well-being and inducing feelings of isolation [81, 170]. Further, rural, low-income, Indigenous, and older populations tend to be disproportionately affected by wildfire events due to pre-existing health conditions or limited access to recovery aid [47, 57, 108], raising issues of environmental and climate justice. Wildfires also compound the threats to clean water already exacerbated by climate change [25] and biodiversity, with bushfires killing or displacing nearly 3 billion animals [39].

However pernicious their effects, wildfires are not entirely harmful; they play a vital role in the natural ecosystem [122]. As a result, effective wildfire management strategies have evolved from mere suppression to a more proactive approach focused on fire control [137, 146, 168]. Nonetheless, there is a critical shortage of fire-prevention and fire-control resources for managing fire and protecting forest ecosystems effectively [90]. The National Interagency Fire Center, for instance, regularly elevates the U.S. to a Preparedness Level 5, indicating that firefighting resources are nearly or completely tapped out [13, 37].

Amid these dwindling resources, technology has been suggested as a potential solution to wildfire challenges [96, 158]. This is particularly true for the broader forest-management sector, which governs wildfire management, where technological innovations like remote sensing and **Geographic Information Systems (GIS)** have been increasingly embraced [6, 66].

2.2 Wildfire and Forest Management Stakeholders and Practices

Our study was initially motivated by the rise in wildfires, prompting us to investigate the increased role of technology in efforts to control, prevent, or mitigate their harms. However, wildfire

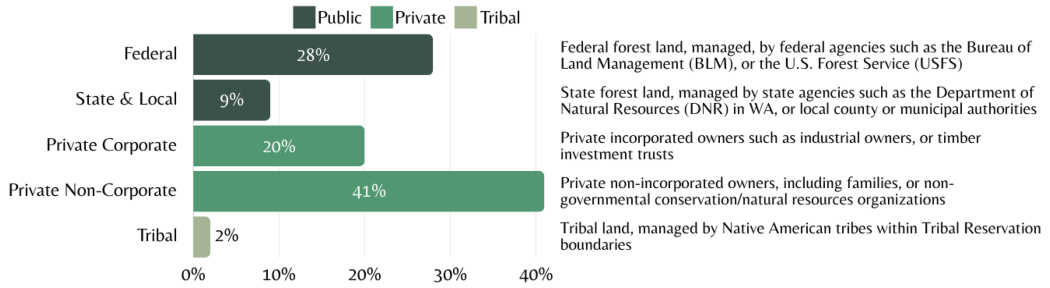

Fig. 1. Fig. 1. *Forest landowners and example agencies in the United States.* Of 765 million acres of total forest land in the U.S., 28% is overseen by federal agencies. Example federal agencies include the USFS, and the BLM [33]; 9% of forest land is overseen by state or local agencies, such as the DNR in Washington state [33]; 20% of forest land is privately managed by corporate landowners, while 41% of the forest land is privately managed by small non-corporate landowners [33]. Small landowners include families and individuals as well as non-governmental organizations [33]. Finally, 2% of the land is managed by Native American tribes within reservation boundaries [33].

management decisions are not made in isolation but rather fall within a broader assortment of management decisions that incorporate considerations of, for instance, water safety, biodiversity, recreational opportunities, and costs of proposed intervention. This led us to expand the focus of our study to forest management as a whole.

Wildfire and forest management generally encompass a range of decisions and practices aimed at sustaining the structure, diversity, and productivity of a forest.[1] These decisions are implemented by myriad actors, including private landowners, government agencies, and Indigenous tribes, each of whom owns and oversees a significant portion of forest land in the U.S. [144]. As Figure 1 shows, private landowners in the U.S. possess 61% of this land, while the federal, and state and local governments oversee 28% and 9% of the land, respectively [33, 107]:

- *Private non-corporate landowners* represent small families, individuals, or non-governmental organizations who own and manage 41% of forest land [33]. Family-owned forests' objectives range from timber harvesting to wildlife habitat management [34].
- *Private corporate landowners*, such as timber companies, own and manage 20% of that land [33]. Their interests tend to be commercially driven, with a focus on timber yield and maintainable forest productivity [136].
- *Federal government agencies*, primarily the **United States Forest Service (USFS)** and the **Bureau of Land Management (BLM)**, oversee 28% of the nation's forest land [45]. These agencies manage under a multiple-use and sustained yield mandate, ensuring forests provide recreational opportunities, safe water, and even timber, while preserving long-term ecological sustainability and public access [120].
- *State and local government agencies*, such as the **Department of Natural Resources (DNR)** in Washington, are responsible for managing 9% of forested areas [5]. Their goals often align with federal priorities but may also respond to local concerns [91].
- *Native American tribes* manage 2% of tribal lands, typically within reservation boundaries [33, 120]. Their forest management practices are frequently guided by cultural, spiritual, and ecological values, promoting biodiversity and sustainable fire regimes [171].

[1] Federal Register: The Daily Journal of the United States Government. Forest Service. Retrieved August 20, 2024 from https://www.federalregister.gov/agencies/forest-service.

Table 1. Common Geospatial Data Sources

Data Source	Data Type	Spatial Resolution	Common Uses	Description
FIA	Ground-based/Survey	Plot-based (varies; generally 1–5 acres)	Tree species, diameter, forest composition, health assessment	*Pros*: Ground-truth data, highly accurate *Cons*: Sparse data, long intervals between collections, limited spatial and temporal coverage
LiDAR	Airborne Laser	1–2 m (point cloud)	Canopy height, biomass estimation	*Pros*: High vertical resolution *Cons*: Expensive, limited spatial and temporal coverage
NAIP	Aerial Imagery	1 m (orthophotos)	Land cover, canopy height	*Pros*: High spatial resolution, annual coverage *Cons*: Limited temporal resolution (only available in summer months)
Sentinel 2	Satellite	10–60 m (multispectral)	Forest cover mapping, vegetation classification	*Pros*: Global coverage *Cons*: 5-day revisit cycle, limited by cloud cover and low resolution
Landsat 8	Satellite	30 m (multispectral)	Forest cover mapping, vegetation classification	*Pros*: Global coverage, historical archive *Cons*: 16-day revisit cycle, limited by cloud cover and low resolution

Land managers apply tactics such as thinning (removing select trees to reduce tree density) and prescribed burning in order to eliminate undergrowth and prevent larger wildfires [125]. A key challenge is determining where and how to apply these tactics, and which tactic to implement [48].

This stewardship is further complicated since a combination of different wildfire management tactics is often necessary. For example, due to a history of fire suppression, tree density has increased, as has the accumulation of understory shrubs and dead wood [48]. Such dense forests, characterized by ladder fuels (i.e., combustible vegetation, like tall grass, shrubs, and low-hanging branches, that allow a fire to climb vertically from vegetation near the ground into the tree canopy), are difficult to manage with controlled burns alone.

As a result, measures such as thinning and bush removal are required first to reduce density and create space between tall canopy trees. Subsequently, small prescribed burns can be applied to remove understory shrubs without significantly harming the remaining trees. Each approach, however, presents tradeoffs. For example, while prescribed burning can result in harmful smoke emissions, thinning is generally considered less effective for wildfire prevention [48].

Finding the correct management strategy could significantly reduce climate impacts. Griscom et al. [71] found that if forests were indeed managed sustainably, they could contribute up to 30% of the Paris Climate Agreement goal toward limiting global warming below 2°C by 2030 because of their critical roles as carbon sinks. Therefore, these management decisions—and the technologies that enable them (Section 2.3)—can yield both ecological and societal benefits.

2.3 Geospatial Technologies in Wildfire and Forest Management

Making informed management decisions requires decision makers to be knowledgeable about the forest's condition by monitoring various forest attributes, such as tree heights and species diversity [159]. This type of data, where attributes and features are related to a specific location on the Earth's surface, is referred to as "geospatial data" [153]. Table 1 summarizes commonly utilized geospatial forest data and sources.

Geospatial tools can support monitoring a forest's condition by, for instance, helping users visualize the prevalence of different tree species across space. Geospatial tools can also support modeling species diversity, extrapolating from areas and time periods when data exist to areas and

times when it does not. Characterizing, visualizing, and modeling forest structure over time can then help inform wildfire management decisions [119].

Traditionally, forest monitoring has involved field workers manually documenting the identity and conditions of trees using direct observations in the wild [65]. For example, the **Forest Inventory and Analysis (FIA)** program conducted by the USFS divides U.S. forest land into survey units that are then visited to record information on tree species or tree diameter among other variables [79]. While measurement protocols vary by region, ground sample plots generally range from one to five acres [79]. Trees in each plot are typically further sub-sampled and counted, and measurements such as tree height are collected [79]. This on-the-ground data collection method is labor-intensive, costly, and time-consuming. Further, the geographic area that field workers can cover is limited [163].

Developments in remote sensing technology (shown in Figure 2) can help fill some gaps in data coverage over time and space. Satellite imagery, though lower in resolution compared to on-the-ground measurements, offers the advantage of covering much larger areas. The most widely used sources of satellite data are the Landsat and Sentinel programs [29, 59]. Landsat, with a 30-meter resolution, has been collecting data in 16-day intervals since the 1970s, while Sentinel 2 offers higher-resolution (10–60 meters) data with a 5-day revisit cycle. To supplement satellite images, **Light Detection and Ranging (LiDAR)** data, collected by drone flights releasing laser pulses over an area to measure distances to the Earth's surface, provides high-resolution point-cloud information that measures canopy height. These data, however, are expensive to collect because it requires planes or airborne drones. Consequently, the data have limited spatial and temporal coverage. Finally, the **National Agriculture Imagery Program (NAIP)** provides high-resolution (1-meter) aerial imagery collected on a 3-year cycle, primarily for land cover mapping. However, it requires an aerial platform and is limited to being collected only during summer months, as this corresponds to the "leaf-on" period of vegetation [138].[2]

Geospatial data have played an expanding role in forest monitoring over the past 20 years [115]. This influx of new data has in turn increased adoption of other technologies for data processing and modeling [166]. These technologies include Google Earth Engine, ArcGIS, and QGIS, as well as Python and R libraries working with vector and rasterized data, LiDAR, or image data analysis, among others [113, 126]. The term *geospatial technologies* broadly encompasses geospatial data and the technologies and tools that enable its processing [143], as shown in Figure 2. Because these technologies are regularly deployed to inform critical management decisions, it is vital to understand how they are integrated and utilized.

Indeed, geospatial technologies could play an increasingly larger role as public land management agencies face increasing scrutiny and political pressure. This year, the already understaffed USFS has been targeted with approximately 3,400 layoffs, amounting to about 10% of its workforce [127]. This exacerbates the discrepancy between the scale of the climate crisis and institutional capacities available to respond. In this context, the development and adoption of geospatial and other technologies, including community-driven work, may be essential to maintaining effective management practices.

Despite increased use of and reliance on geospatial technologies, HCI researchers lack a clear understanding of specific obstacles faced by domain experts, such as forest ecologists, who often work in land management [177], especially since the availability and accessibly of geospatial data for forest and wildfire management varies based on end-users. Prior HCI work indicates that geospatial data analysis presents unique challenges distinct from conventional data analysis because it (1)

[2]TERRAINMAP Earth Imaging LLC. Pancroma Satellite Image Processing. NAIP Multispectral Analysis. Retrieved August 20, 2024 from http://www.pancroma.com/NAIP%20Multispectral%20Analysis.html#:~:text=The%20intended%20purpose%20of%20the,with%20virtually%20no%20cloud%20cover.

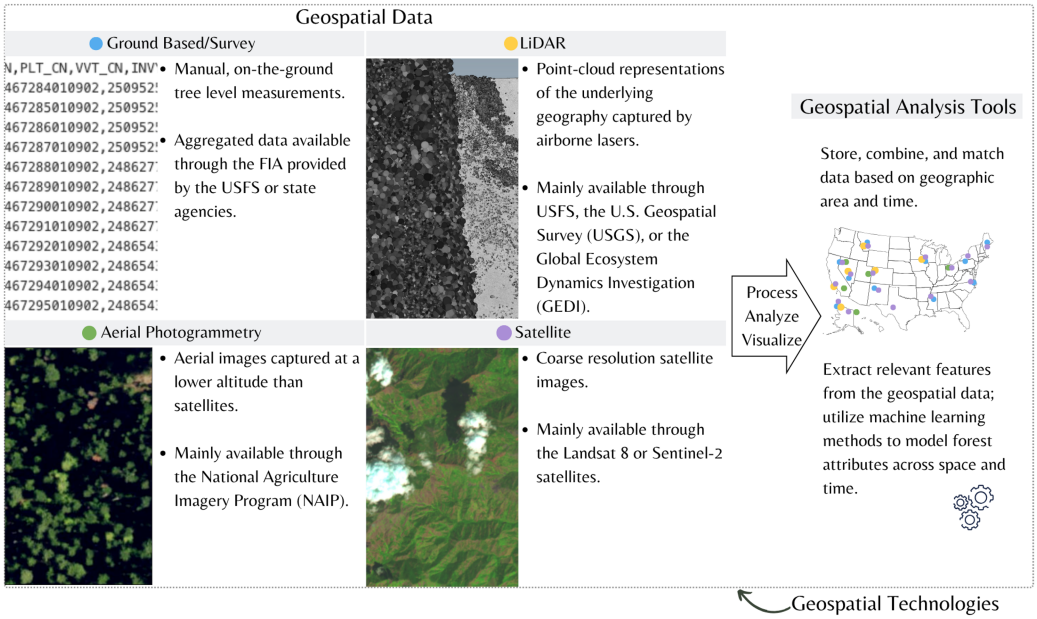

Fig. 2. *Key Terms and Definitions.* "Geospatial data"—i.e., data related to a specific location on the Earth's surface [153]—can be derived from satellite images, LiDAR scans, aerial photogrammetry, or on-the-ground measurements [14]. The data are then processed, transformed, modeled, analyzed, and visualized. These data and tools that enable its processing are referred to as "geospatial technologies" [143].

utilizes data in relation to spatial and temporal contexts and (2) adds complexity to the processes of reasoning about and analyzing the data [21, 129]. Work by Roth et al. [133] and Andrienko et al. [11] emphasize the need for tools that are both cognitively accessible and support the complex spatial-temporal reasoning [12, 102], which are inherent to forest management tasks. They argue that interactive maps and visualization systems continue to suffer from minimal uptake among target users due to these challenges [12, 102].

Untrained users often find the complex, map-based interfaces of these systems daunting [116, 164]. This is especially salient since many ecologists have self-taught computer science/programming skills and may be unfamiliar with geospatial systems [35]. Moreover, research has observed that differences exist between computer scientists and ecologists in their relationships to data [167]. Tulia et al. [163] document the disconnect between massive volumes of raw data collected for ecological research and their users' capacity to process and analyze it comprehensively and efficiently.

We expect that the same disconnect exists in wildfire and forest management given the challenges in geospatial data analysis; however, this assumption remains largely unexamined. A literature review of 40 HCI papers that examine public-facing climate change issues revealed that only two addressed land management [60]. Our research seeks to narrow this gap by examining the utilization of geospatial technologies in the domain of wildfire and forest management, identifying specific challenges that emerge in their use.

2.4 Opportunities for HCI

Though wildfire and forest management have increasingly integrated technology, this broad domain has received limited attention from HCI researchers. However, the HCI community has, in parallel, aimed to more broadly expand its role in addressing climate change [28] through the inception of SHCI in 2007. Nonetheless, SHCI has faced challenges in building momentum [76, 89].

A prevailing view suggests that SHCI should change its focus from persuasive technologies designed to affect individual behavioral change—which DiSalvo et al. [55] showed accounted for 45% of the corpus—to instead integrate knowledge from diverse fields and shift toward systems thinking to better understand and address the complex, multi-scalar challenges of sustainability [28, 111, 140, 141]. This is also consistent with HCI and CSCW works arguing for enhanced engagement with policy and policy-makers and systems at large [53, 77, 86].

Moreover, Soden [147] describe how climate change discourse frequently occurs outside the traditional realms of HCI, while Bremer et al. [28] highlight that this might be due to the nature of SHCI research. They maintain that focusing on documenting systems and generating contextual understanding of technology, while valuable, makes SHCI's impact on climate change difficult to measure and might instead shift the responsibility of concrete work onto others [28]. Our work seeks to answer these calls in three ways: (1) by considering an under-explored domain of wildfire and forest management and (2) by examining the greater socio-technical systems within which geospatial technologies for wildfire and forest management are embedded, and (3) by proposing an HCI research agenda that describes concrete future research directions that could pave the way for more measurable contributions. This agenda could also couple the technological challenges of wildfire and forest management with ongoing, relevant, and usability-focused HCI and computer science discussions.

3 Methods

Our aim was to understand (RQ1) the use of geospatial data analysis technologies and (RQ2) the socio-technical system in which those technologies are used. To this end, we conducted interviews with 12 participants from wildfire and forest management, then coded, and analyzed the interview data as described in the following sections.

3.1 Participants and Recruitment

In total, we interviewed 12 U.S. participants—2 from academia, 3 from non-profit organizations, 3 from industry (for-profit organizations), and 4 from public land management agencies such as the USFS. Interviewing practitioners from these diverse sectors provided a broad array of perspectives and priorities and allowed us to examine how issues raised by these different individuals were interrelated.

The participants worked across multiple project areas, with many engaging in more than one project area: 8 focused on wildfires (e.g., modeling where wildfires occurred or how they affected ecological forest structure), 8 on stand structure and forest attributes (e.g., tree size or age), 3 on forest dynamics (e.g., tree mortality from bugs or disease), 2 on recreation (e.g., number of visitors to public lands and accessibility of recreational resources), and 1 on forest composition and diversity (e.g., distribution of species).

Several participants reported collaborating closely with rural and Indigenous communities in their work (i.e., P1, P2, P5, and P7). However, individuals from these communities were not interviewed. This is a limitation of our recruitment approach, which primarily reached those managing forests that by a vast majority are owned by public and private organizations. This gap also reflects a broader systemic issue and under-representation of Indigenous people and Indigenous-led organizations in land management roles. See Limitations (Section 6.3).

We recruited participants by contacting researchers at our university whose research addressed questions related to wildfire and forest management, and we subsequently applied snowball sampling [23] through which participants recommended other contacts. We screened these recommendations based on the individual's role and their level of engagement with the topic. This approach engaged people who represented a wide range of subject areas and geospatial technological tools, as shown in Table 2. We chose not to disclose the participants' exact titles to protect anonymity.

Table 2. Participants' Role, Affiliations, and Project Areas

	Role	Affiliation	Collaborates With	Project Areas
P1	Forest Ecologist	Academia	Small Landowners Public Agencies Local and Rural Communities	Forest Attributes Forest Species
P2	Data Analyst	Non-Profit	Indigenous Communities Small Landowners	Forest Attributes
P3	Research Scientist	Academia	Public Agencies	Forest Attributes Wildfires
P4	Senior Director	Non-Profit	Small Landowners Large Landowners	Forest Attributes
P5	Research Scientist	Public Agency	Public Agencies Local and Rural Communities	Recreation Wildfires
P6	Program Specialist	Public Agency	Public Agencies	Forest Attributes Wildfires
P7	Forestry Engineer	Non-Profit	Indigenous Communities Public Agencies	Forest Attributes Forest Health
P8	Research Scientist	Public Agency	Public Agencies	Recreation Wildfires
P9	Research Scientist	Industry	Public Agencies	Forest Health Wildfires
P10	Forest Ecologist	Industry	Public Agencies	Forest Attributes Wildfires
P11	Research Scientist	Public Agency	Public Agencies	Forest Health Wildfires
P12	Lead Data Scientist	Industry	Public Agencies	Forest Attributes Wildfires

3.2 Procedure

One of the 12 interviews took place in person, and all others were conducted remotely over Zoom or Microsoft Teams. All interviews were recorded for subsequent analysis; the audio recordings were then transcribed using Google's Speech-to-Text AI[3] and manually verified by the authors.

The semi-structured interviews began by asking participants to describe a current project to understand the general problem in wildfire and forest management they were trying to solve. Depending on their response, we followed up with questions about the data they required for the described project, how they acquired that data, and what challenges they encountered with this step. These questions elicited a better sense of their information needs. We then asked about the data analysis steps, and how technological tools fit into their workflows, which stakeholders they collaborated with, and whether and how this contributed to wildfire and forest management decisions. The interviews lasted between 30 minutes to an hour, and participants were not compensated.

[3] https://cloud.google.com/speech-to-text.

The interviews and procedures were submitted to our institution's Institutional Review Board. Following the review process, our study received an exempt determination because there was minimal risk to participants. This was because our interviews were focused on professional expertise rather than personal or sensitive experiences. However, we recognize the potential sensitivities involved in discussing forest management practices tied to cultural or political viewpoints. We treated transcribed text with care, including removing material upon request and anonymizing identifiers.

All participants were asked for consent before recording the interview. We also reminded them that their consent could be withdrawn at any point. One participant felt discomfort about including a certain section of their interview in the analysis, so we deleted that section from the audio file before submitting it for transcription. Interview quotes in the remainder of this article have been lightly edited for readability (e.g., removing repeated words).

3.3 Data Analysis

We followed an inductive thematic analysis approach [27]. We first used a collaborative, qualitative open coding process [156]. Three authors analyzed five interviews separately and generated codes based on the quotes and ideas expressed. These codes were then combined and further refined collaboratively by consolidating some or breaking others out. Once agreement was reached, a codebook was created based on the identified codes. These broadly covered (1) the project area, (2) current geospatial technologies utilized, (3) challenges, and (4) ethical considerations. Three researchers then applied this codebook to all interview transcripts. After coding the data, the authors met to identify potential themes, which were iterated upon another three times until agreement was reached.

4 Findings: Into the Woods

Our interviews uncovered five key themes, which we present below. The first four address *the socio-technical systems* in which geospatial technologies are situated. The fifth theme delves deeper into *the specific technical challenges* participants face with geospatial technologies.

4.1 Complex System of Stakeholders

Our interviews revealed that the wildfire and forest management landscape is comprised of a complex system of stakeholders. We find that all participants collaborated with external organizations or agencies, forming a robust network of interconnections.

Participant P10, in industry, noted their collaboration with public entities like the USFS as well as non-profit organizations, saying that they "ended up partnering with the (US) Forest Service…but also places like Nature Conservancy, other nonprofits, more state or local level resource agencies." This establishes a *connection between industry and land owners and managers*.

Similarly, P6, affiliated with a federal agency, mentioned their collaborations with state agencies and local groups: "[The federal agency] works with state and private entities, tribes, and other groups depending on the goals." This, in turn, highlights the *connection between federal agencies and various landowners and managers*.

Additionally, P1, an academic who works with state agencies and small non-corporate landowners, stated: "We have some collaborative projects with the Department of Natural Resources. Sometimes, we're either engaged in small landowner-related activities and/or workshops." This reflects the *connection between academia, land owners and managers*.

Importantly, these varied stakeholders are connected through their shared needs and uses of geospatial data and technologies. The connections between industry and landowners, academia and landowners, and landowners themselves, shown in Figure 3 and discussed below in subsequent

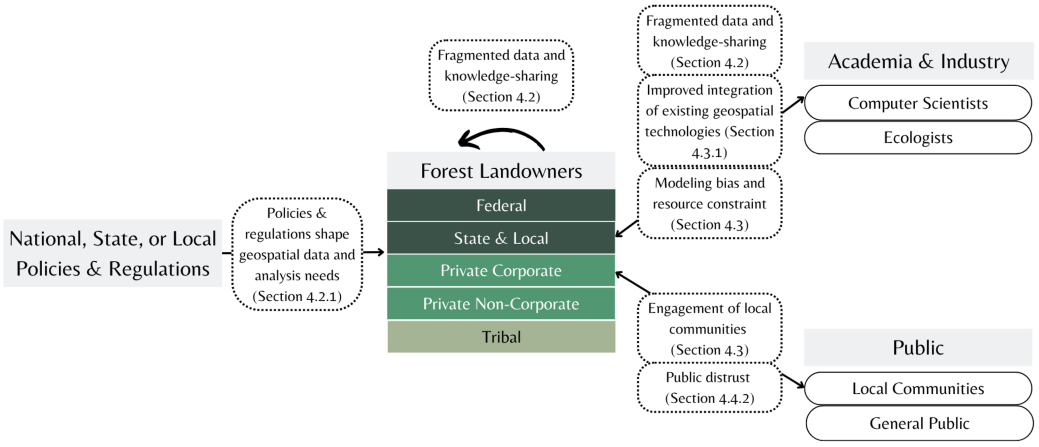

Fig. 3. *The socio-technical system of geospatial technologies.* National and state governments set policies and regulations that land owners and managers must follow (Section 4.2.1). To adhere to those policies and manage forest land effectively, landowners and managers and other stakeholders in academia and industry share data and knowledge (Section 4.2). Landowners and managers also seek to engage computer scientists in industry and academia (Section 4.3.1) as well as local communities and the public (Section 4.4.1). Input from academia and industry (Sections 4.3.2 and 4.3.3) and from the public (Section 4.4.2) is fed back to landowners and managers. We describe the challenges that emerge in these interactions in Sections 4.2–4.4. Note: This figure is intended to visualize the socio-technical system of geospatial technologies as raised by interviewees; the purpose is not to provide a comprehensive or definitive depiction of the management and governance system.

themes, describe the socio-technical context of geospatial technologies for wildfire and forest management. The intricate web often gives rise to fragmented and undocumented knowledge.

4.2 Fragmented Knowledge

A contributing factor driving collaborations between land managers, as well as with academia and industry, is the disparity in geospatial data, information, and resource access among stakeholders. Our second highlights these disparities and their causes.

4.2.1 Gaps in Resources and Varied Policy Requirements. Our interviews revealed *significant geospatial data, information and resource limitations*. For example, P1, an academic, noted the severe challenges small landowners face due to limited data handling capabilities, necessitating external support to make geospatial data available and usable:

> "They [small landowners] just can't do it. Now, we [in academia] collect information, I don't know how many tens of terabytes, and then getting from the step of having that data to it properly processed and in the hands of somebody where they can use it in a useful way is often really the key step, right?"—*P1*

Participant P8, a USFS employee, echoed this sentiment, describing that even among federal land managers, different agencies like the BLM face challenges due to a lack of on-the-ground geospatial data compared to USFS: "Other federal agencies do not have as much on-the ground data as we have. So in the Bureau of Land Management, which is a big agency in the Western U.S., they have hardly any on-the-ground information."

This disparity and variation in access often arose because the funding and costs of data collection presented significant constraints. As P8 observed: "For the Forest Service, yeah, it's mostly cost.

It's very expensive to collect the data on the ground. We just don't have the funding to do it every year."

Another factor leading to data and information fragmentation between stakeholders is that *any one stakeholder has disparate geospatial data and information needs, heavily influenced by policies and regulations.* For example, P2 described how small landowners need to provide geospatial data and map layers to ensure they are complying with specific regulation requirements: "To manage their forest, [small landowners] have to submit a forest management plan. For that, they are asked to provide several layers of information."

Similarly, P3, who collaborated with the public sector and supported geospatial data analysis efforts, stated that the nature of their work was shaped by a new regulation aimed at improving forest conditions:

> "The genesis of our current work is for the [Washington] Department of Natural Resources. They have a 20-year Forest Health Plan they are implementing, which is focused mainly on east side forest health issues, bark beetles, fire, droughts, mortality in general."—*P3*

In short, we found data, information, and resource fragmentation among stakeholders, with challenges such as limited data handling capabilities and uneven data availability. These challenges are exacerbated by data collection costs and varying governmental policy requirements.

4.2.2 Localized and Undocumented Knowledge. Collaborations often formed between stakeholders to help overcome this situation. Our findings reveal that practitioners from diverse sectors frequently *worked together, specifically to combine various geospatial data sources.* For example, P3 described how forming partnerships helped them to collect more data:

> "While we were doing all that work for all the small forest landowner constituents, we built up a loyal following in terms of being able to collect data and provide information to the legislature in state agencies."—*P3*

In addition to working with small landowners, P3 further highlighted the need to collate geospatial data from as many sources as possible. They noted that groups ranging from both public agencies to tribes help provide necessary geospatial data:

> "So these plot networks, where people go out and measure the trees…stand in a circle and get all that information. So we've been gathering all that from as many different sources as possible. There's lots of different folks that are doing that, the Department of Natural Resources, the Forest Service and their Forest Inventory Analysis program, the Bureau of Land Management, there's tribes and there's individual small landowners, too, that contribute this kind of information."—*P3*

Despite considerable collaboration among stakeholders, gaps in data and information persisted. This is because *much of the knowledge is specialized, localized, and not documented.* Institutional knowledge was often held by seasoned professionals in agencies. As P5 explained: "You have a lot of people working at the local level who really get to know the landscapes and resources that they are working with."

Participant P3 also supported this by stating that, "It's all gonna be just institutional knowledge that's held within a few old-timers at the agencies." Thus, *on-the-ground knowledge is often fragmented,* making knowledge sharing challenging. Further, this fragmentation results in situations where data and reports from diverse sources are informally collected and not documented, leading to *management decisions that are not standardized or replicable.* As P5 describes:

> "The way that data is collected is either informally or formally: it's not necessarily compatible. So you end up with these reports, and people refer to them as like 'stapled together.' So you will have one specialist's report and then another, and then it just gets stacked up together."—*P5*

The *lack of documentation of institutional knowledge* further adds to fragmentation because the decisions a certain land manager arrives at might be challenging to replicate. P5 added that, "there's a lot of discretion in that local decision making…it's not always value-explicit in what [the district manager] decides to prioritize or not." This further complicates knowledge sharing, leading to continued data and information limitations.

4.3 Data Expertise, Modeling Bias, and Resource Constraints

Participants expressed the need to *integrate* geospatial technologies and share geospatial technology *expertise* with computer science experts, but participants raised concerns about *model bias* and the *lack of sufficient resources.*

4.3.1 Improved Integration of Existing Geospatial Technologies. Participants utilized various **Machine Learning (ML)** tools to analyze geospatial data. For instance, P2, P3, and P12 developed models that were trained on geographic areas where geospatial data were available. These models then predicted forest attributes in regions lacking data. Still, *participants expressed a lack of integration of existing geospatial technologies.* They wanted to share knowledge gleaned from these technologies, were keen to integrate newer technologies, and they sought collaborations with computer science experts. P3, self-taught in data analysis, shared that although they currently use ML models, such as boosted regression trees, they see potential to integrate more advanced technologies to expand their capabilities:

> "We're using these boosted regression models at the moment, which sort of fall into the machine learning category, but they're kind of on the lower entry point to the whole machine learning world. We think there's a lot of opportunity probably to expand beyond these boosted tree models."—*P3*

Participant P3 also expressed a desire to collaborate with computer science experts in these areas, wanting to explore models like neural networks. They stated: "Our hope is to attract a whole different cadre of researcher to dig into it."

Similarly, P7 described how the growth of remote sensing data provided a good opportunity to connect with the computer science world:

> "I'm realizing that I regret not learning more about computers, coding and things like that. Because the use of satellite data, big data, machine learning, it is coming slowly. But it's coming. It's becoming transformative like in anything that you do."—*P7*

In essence, participants discussed how the geospatial technologies they want to integrate already exist. The challenge lies in the uptake and integration of such technologies. To address this need, participants sought a better way to share knowledge and collaborate with computer science experts.

4.3.2 Apprehensions about Modeling Bias. Though enthusiastic about incorporating more advanced models, participants voiced *significant concerns over bias in ML models since the outcomes of these models can shape management practices, policies, and regulations.*

A common modeling problem in wildfire and forest management is performing land-use and land-cover segmentation. This modeling approach predicts whether a certain geographic area should be classified as forest, grassland, agriculture, and so on. These delineations can inform where forest boundaries lie, which can then be used to identify neighborhoods that might be most affected

by wildfires or various forest treatment plans. P11 elaborated on how the outputs from these land cover segmentation ML models can be biased:

> "The canopy cover for my program is very important because it is used to determine whether a piece of land is going to be labeled 'forest' or 'non-forest.' And that comes with regulations, comes with management practices. And there is this global 10% cut off. So if your piece of land…can sustain for a prolonged period…10% canopy cover, then that is considered forest land. If you're having an assessment methodology and it uses LiDAR, it is biased. And in reality, the canopy cover is 8% and because of the bias, your estimate is 14%, that automatically gets a lot of acreage. That's the reality. It's not a forest, but it's labeled as 'forest.' And that's a problem."—*P11*

These results of model classifications can be problematic since they inform management practices, including where resources and funds are allocated. P11 further explains that classifications derived from models based on geospatial data, particularly remote sensing data, can inform compensation for those on the ground who have experienced damage to their infrastructure and that the output of the models can be high stakes:

> "You have a natural disaster. All these farmers need to be compensated where they lost their crops and lost infrastructure. Well, if you use the standard, which is the Landsat and the European Sentinel satellites, those together, they have an interval of 8 days…Where the flood came in, it didn't last too long. It stayed there for a day or two…So the guys that look at these things say 'Hey, look we're using Sentinel. The area that you are applying for funding is not affected. You're lying. And therefore you're not getting the money.' And we're talking about a lot of money, like hundreds of millions a year."—*P11*

Participants raised concerns that information from biased modeled outputs might not only affect management practices and compensation, but also impact real people and communities. They emphasized *the importance of considering social justice when generating modeled maps.* For example, P7 shared how the maps and resulting management practices could potentially create obstacles or cause problems for local communities, highlighting the real-world impact these tools have on everyday lives:

> "Sometimes, those maps are done without any attention towards what is on-the-ground. There's people there, and then you wanna just put up layer of trees, and then people get excluded; they're kicked out, and…the story goes not in the best way."—*P7*

Overall, participants expressed concerns that bias in modeling could lead to incorrect management practices and resource allocation. They highlighted that such biases not only affect regulatory outcomes but tangibly impact communities.

4.3.3 Better Models Do Not Equal Better Land Management. In addition to bias, participants also recognized that technologies must be developed within the constraints of the socio-technical world in which they operate. Despite the prevailing *trend in computer science to prioritize more accurate and higher-resolution solutions, many participants cautioned against this approach.* Instead of highlighting accuracy, P7, for example, described how the output of the ML models should focus on interpretability to be actionable. However, the models sometimes fall short:

> "I think that one of the benefits is being able to process large amounts of data. I know a lot of people see machine learning as *the* solution. Sometimes, the machine learning gives you an output that doesn't have any, you know, ecological logic or social governance."—*P7*

Similarly, P11 observed that as geospatial technologies develop, they do provide some improvements through increased accuracy and resolution. Still, these improvements do not offer the full solution to best wildfire and forest management practices:

> "Then every time there is a new technology coming up, because when I started, the resolution was 30 meters or 500 meters or something like huge…Everybody said, 'Oh, we're gonna do all management perfectly.' Then, we got LiDAR, 'Oh, now we are gonna do everything perfectly.' It happened too many times to me to say that 'Well, yeah, it improves, but it doesn't do everything.' Because the thing is that with the capabilities also, the expectations go up. People want more."—*P11*

This is significant since *better models do not necessarily translate into better land management practices*. Funding and resource constraints on actual work that can be done on the ground constitute a major limiting factor, as well. P1 described this phenomenon, recounting how improved geospatial data accuracy or resolution is not meaningful if land managers cannot act on the information:

> "Let's just say, annual or sub-annual resolution of this kind of data gives very quick awareness of problems and [forest] changes. And then, of course, it would be the capacity to be able to respond to that as well, right? Like how much money do the foresters have? They don't even have enough money to fight fires, you know, let alone do anything else, right? That's kind of where these political realities sort of trump the utility of having any more information."—*P1*

Participant P6 also discussed the limited capacity to manage the land proactively: "We're looking at high severity burns that we are completely unprepared for, and we haven't been able to treat forests proactively."

Thus, participants emphasized that better models alone do not ensure better outcomes since funding and resource limitations pose a more severe roadblock to effective management implementation and response.

4.4 Engaging the Public and Local Communities

Participants highlighted both the significance of and existing gaps in socio-ecological research and emphasized the critical need to involve the public and local communities in decision-making and research processes. However, efforts to engage the public are hindered by distrust.

4.4.1 Impact on Local Communities. Participants recognized that many existing management and research strategies are aimed at improving *either* the social or ecological systems, with little work addressing the intersection of the socio-ecological. For instance, P5 explained: "The social and ecological dynamics tend to be integrated, so thinking about dynamics between both and understanding the interaction between them. And I don't see a ton of research happening on that."

To address this gap, participants expressed *the need to involve local communities in management decision-making and research.* P5 went on to observe that a lack of involvement of local communities could be harmful since they are often the most directly impacted:

> "It's related to, if there's a fire event, if there's a flooding event, if there's any natural disaster or human-induced disaster that might affect people and vulnerable families, then if you don't have any physical way of knowing where they are or means of communication, then those people are going to be at a much higher risk of being harmed."—*P5*

Participant P10 echoed that local communities and tribal community members often bear the brunt of natural catastrophes like wildfires: "And I mean probably unsurprisingly, a lot of the fire risk comes from [fires on] National Forest Lands that are moving onto tribal lands."

Similarly, P9 expressed that it is important to re-consider who technologies and technical tools are created for. They argued that local communities should be the primary stakeholders of technologies because they are most impacted by them and by the resulting land management decisions:

> "You and I can create an app or a tool; we can build an informational book or a guide or whatever; but at the end of the day, if we're talking about forests or wildlands, places outside of the city that we want to manage, the people who are the stewards that live in those communities and have to live with the consequences directly are the people that we should be arming and focusing on as our 'quote' customers."—*P9*

In sum, participants noted a lack of management strategies and research devoted to understanding socio-ecological dynamics of wildfire and forest management. Yet, they felt it imperative to involve local communities when designing technologies that inform management decisions. Participants also urged additional research to improve socio-ecological systems as these communities are most affected by land management decisions and natural disasters.

4.4.2 Public Distrust. In addition to local communities, another important stakeholder for practitioners is the general public. Public support is required for making land management decisions, particularly on public lands. As P8 explained: "Part of what the law says we must do is that we need to manage forests with public involvement, so we can't do things on our own without listening to the public at all."

However, challenges emerged in forming relationships that are open, genuine, and facilitate a two-way dialogue with the public. Participants felt that the public viewed wildfire and forest management with general distrust. P1 explained that public distrust in land management decisions came from a sense that management decisions were driven by a profit motive, stating that:

> "We have a really pretty high potential to increase the amount of carbon up-take from the atmosphere in forests through improved forest management, and simultaneously a complete lack of trust in the public and the ability of forestry to provide such a thing that is presumed to be unethical and money-grabbing."—*P1*

Participants highlighted the importance of public involvement in land management decisions. Yet, they faced challenges in building trust since the public often skeptically viewed wildfire and forest management efforts as profit-driven.

4.5 Lack of Expertise and Technical Challenges

While prior sections focus on the general socio-technical context of geospatial technologies in wildfire and forest management, this section examines the specific technical challenges participants identified. In line with prior research [35], *many practitioners felt they lacked expertise in geospatial technologies*, with most coding skills being self-taught. P10 explained that their coding knowledge was acquired with no formal education:

> "I dropped out of my computer science class major so I could be an environmental science…person. So a lot of us are using self-taught coding principles or not principles—not strong, fundamental principles of coding, often cobbling together multiple tools."—*P10*

Participant P11 also mentioned that much of their programming background was self-taught: "Everything about programming and things like that was self learning."

This lack of expertise was compounded by the fact that *the processing of complex, large, and disparate geospatial datasets could take years.* Participants had to assemble their data from varied sources; subsequently, they cited that combining and processing data in different formats was time-consuming. P3 described how the process took one or two years despite working in teams:

> "So taking all of that and putting it into a normalized authoritative source for understanding what's out there in this plot data and then be able to use that plot database. This took, I don't know, a year or two probably?"—*P3*

Participant P12 had a similar experience, stating that: "The processing of all this information is like out of control. It's like fully insane. So one year at this current granularity."

Participants attributed the lengthy data processing step to the *sheer magnitude and complexity of the data*. P12, for instance, mentioned that their dataset was 900 terabytes, while P2 stated that aerial image and satellite data are memory-intensive:

> "Pulling the data takes a lot of time because it's information that uses a lot of space. It's a lot of information. For example satellite imagery like Sentinel has 10/12 bands, and it's 10-meter resolution. So everything you download consumes a lot of space, and same with Landsat."—*P2*

Many individuals we interviewed cited feeling overwhelmed due to the amount of data they needed to wrangle. A key bottleneck was the participants' *lack of expertise in managing large datasets*. P10 explained that their data had reached such a large scale that it required different big-data skills than they were accustomed to using:

> "I never really encountered situations before where my projects were of such scale that I couldn't wait 5 minutes for my code to finish. Like now, we're encountering things where code takes days. If it were to run in the way I coded it, it just would never finish. Cause there's 1 million trees on this landscape, you know?"—*P10*

Participant 12 echoed this challenge, stating that:

> "So processing, collecting all of these data at that scale and getting them into the database and regularly updated, much less all of the modeling work at that spatial scale, I think there's going to be another 'How do we even do that?' question."—*P12*

Similarly, having to deal with disparate data sources means that each data source covers different geographic areas, is collected at different times, or varies in resolution. Here, too, participants reported *not having expertise in resolving dataset differences and data harmonization*. P12 mentioned how important it was for data to be aligned both in time and in space, but that this was a more significant challenge than anticipated:

> "And when we use multiple datasets that becomes an issue, like if you use something like intersecting NAIP imagery and Sentinel imagery, one pixel of the Sentinel may represent 10 pixels of the NAIP, right? Because it's just bigger and of course, and it all has to like align correctly with each other, and in time, too. So there's like a whole time-space element of these data that, like people kind of neglect."—*P12*

The lack of expertise also complicated efforts of participants to engage with current research in geospatial technologies, with *a key challenge being staying current with the latest advances in computer science*. For instance, P2 described that accessing and understanding the most relevant research in areas such as computer vision was not readily achievable:

> "There is not that much [literature] for remote sensing…if you want to use a vision transformer, then there's not much on that since it's relatively new. There's not many examples that you can find on the Internet like people that already implemented a problem like the one that you are trying to implement."—*P2*

Many practitioners felt they lacked formal expertise in geospatial technologies, relying mostly on self-taught coding skills. The immense complexity and volume of data resulted in an ironic

situation—participants had both "too little" data, requiring combining data across many disparate sources, and "too much" data, that was memory-intensive and required lengthy processing times. Participants also struggled to harmonize the formats of disparate data sources. Finally, they expressed difficulty adapting existing data science methods specifically to their geospatial analysis needs.

5 Where HCI Can Contribute to Wildfire and Forest Management

The themes emerging from our interviews highlight the need for more communication and knowledge sharing among landowners, land managers, and stakeholders in academia and industry. There is a strong desire by landowners and managers to engage the public in wildfire and forest management efforts. We draw insights from our findings to inform future research directions for HCI, summarized in Table 3.

Since 1986, public land management has been characterized as a "wicked" problem, i.e., a complex issue that reflects deeper systemic challenges and lacks a clear or immediate solution [10, 43, 104], especially in the context of wildfire management [36]. Therefore, no single solution we propose below is sufficient to address the complexity of the issue. Instead, we envision areas in which HCI researchers can contribute to long-term visions that support wildfire and forest management. In many cases, we see HCI's role as supportive but crucial, offering perspectives that can enhance broader management efforts. We echo Kuznetsov and Tomitsch [94] in stating that "wicked" problems are often of particular interest to HCI, which is inherently an interdisciplinary field.

5.1 Navigating Diverse Stakeholder Needs

As described in Section 4.1, forest and wildfire management involves a diverse range of user groups, from small landowners to large government agencies, each with distinct needs and capabilities. Stakeholders operate under diverse constraints, including policy mandates, funding limitations, and gaps in geospatial expertise. They are typically interested in only a small subset of geospatial data and technologies relevant to their specific needs [73]; excess data can distract and lead to technical and cognitive overload [31]. HCI research is well-suited to address the diverse needs across stakeholders by tailoring tools to users' specific contexts and priorities.

How Do Small Landowners Access, Use, and Experience Geospatial Technologies for Land Management? How Can These Tools Be More Equitably Designed and Deployed to Support Their Diverse Needs? Small landowners represent an important but understudied user group. Though we interviewed people from non-governmental organizations and universities who support them with geospatial tools, small landowners face distinct challenges compared to larger land managers. They oversee smaller parcels for which remotely sensed data may be too coarse or irrelevant [134]. It is unclear which, if any, technologies they rely on in their decision-making. For instance, Bettinger et al. found that half of the small landowners they surveyed used no digital tools for forest management [22]—but why? A systematic characterization of geospatial technology use cases among small landowners could fill a critical research gap.

Further, there are discrepancies in which technologies landowners are able to access; differences in digital literacy create inequalities in who can effectively utilize these geospatial tools and how [22]. Designing meaningful technological interventions requires an understanding of varying user skills and knowledge sets, which critical HCI studies in environmental justice [16] and racial justice [118] can help further explore.

Table 3. Research and Design Opportunities

5.1: Navigating Diverse Stakeholder Needs
Background: Stakeholders in forest and wildfire management operate under diverse constraints and have unequal access to geospatial tools. *Opportunities*: — Understand how small landowners use or fail to use geospatial tools. — Investigate how policy shapes technology needs.
5.2: Developing Knowledge Exchange Tools
Background: Knowledge about on-the-ground conditions is unevenly documented, often informal, and difficult to integrate into data-driven systems. *Opportunities*: — Use ethnographic methods to document informal knowledge practices. — Build field tools for knowledge documentation. — Develop collaboration platforms that support shared planning.
5.3: Developing Tools to Facilitate Decision-Making
Background: Managers face high complexity in land conditions and data sources, and decision support tools remain underutilized. *Opportunities*: — Study how composite indices influence decision-making. — Investigate embedded ethics in decision support tools. — Explore how digital tools mediate forest boundaries and shape perceptions.
5.4: Engaging Local Communities and the Public
Background: Local communities desire engagement but face barriers to sustained involvement and equitable participation. *Opportunities*: — Examine impacts of participatory mapping and storytelling on trust and understanding. — Investigate crisis communication systems and citizen science adaptations.
5.5: Bridging Gaps Between Computer Science and Wildfire and Forest Management
Background: Technical gaps and cultural divides limit collaboration between forest managers and computer scientists. *Opportunities*: — Study usability across the full geospatial workflow. — Understand collaboration gaps between computer science researchers and practitioners.

Moreover, some geospatial tools to support small landowners exist. One example is Land Mapper,[4] an online platform that visualizes geospatial information over smaller geographic units, i.e., tax parcels, where most commonly available public maps operate at larger geographic scales. The reduced geographic scale of data better fits user needs. Land Mapper also provides valuable meta-information about the land parcels, including which watershed the parcel is located in, helping landowners better understand the environmental context of their areas of interest.

Nevertheless, these tools are not customized to enable small landowners to extract information that is relevant to their diverse management goals. HCI researchers could apply qualitative and quantitative methods, including interviews, workshops, and user studies, to identify information gaps for small landowners and how these tools could be supplemented and customized.

[4] Washington State Department of Natural Resources. Landmapper. Retrieved June 3, 2025 from https://washington.landmapper.ecotrust.org/landmapper/.

How Can HCI Help Design Tools that Integrate Policy Information? In Section 4.2.1, we identified that policy requirements drove many of landowners' geospatial technology needs. Thomas et al. [157] point out that while HCI research has made significant strides in environmental domains, prior HCI research has not focused on supporting the nexus of environment and policy. This gap opens opportunities for HCI researchers to more deeply investigate the socio-technical realities of policy-driven technology adoption. Future research could study the ways in which policy mandates shape various landowners' perceptions, needs, and barriers related to geospatial technologies.

5.2 Developing Knowledge Exchange Tools

We uncovered that knowledge about on-the-ground conditions is frequently not documented or held only by local stewards (Section 4.2). In this context, knowledge is distributed unevenly across individuals and groups; further bias exists in availability of both information (and lack thereof) and the data-driven models and technological tools that track large-scale environmental information [92]. There are opportunities for future HCI researchers to synthesize these diverse viewpoints, experiences, and expertise.

What Geospatial Information Is Documented and Collected Formally versus Informally? Ethnographic research in HCI could be a valuable method to uncover undocumented and informal information practices that shape decision-making in land management. While Perovich et al. [123] have highlighted the value of ethnography for understanding information flows among people managing marine ecosystems, similar methods could be extended to people involved in wildfire and forest management. By working closely with district managers at federal agencies, researchers could systematically document how information is collected, processed, and shared, distinguishing between formally archived data and *ad hoc*, experience-based practices that often remain invisible. Of course, not all knowledge can be systematized, nor should it be, through technological means. However, such ethnographic mapping of the information space [20, 128] could inform more context-sensitive approaches to technology design that support knowledge exchange.

What Field-Based Tools Support the Documentation and Integration of Localized Knowledge? Future HCI research could focus on developing tools that forest managers could use directly in the field. Steup et al. [152] explored how, in the agricultural context, local farms could leverage video-sharing platforms to promote their practices, educate others, share information, and foster community among farmers [152]. Similarly, Standley et al. [151] examined how the Kuku-Thaypan group, Traditional Owners of lands in Far North Queensland, utilized video-based digital media to record, demonstrate, and communicate their local knowledge, situating these media technologies within the physicality of their lands.

Similar tools for synthesizing knowledge in wildfire and forest management in the U.S. context and for a variety of stakeholders remain largely unexplored. HCI researchers could consider systematizing and documenting knowledge of locals by analyzing journals or annotations similar to the work of Nundloll et al. [117], or by looking for the most effective ways to incorporate local knowledge into existing geospatial analysis tools, such as GIS software and maps [162].

How Can Collaborative Tools Be Designed to Support Communal Data Sharing and Planning? Finally, though landowners oversee individual properties, their management actions are interconnected; the effectiveness of wildfire mitigation depends on coordination across property boundaries. Baumber et al. [17] argue that online collaboration tools can serve as platforms for communal data sharing and decision-making. They present a case study in which small-scale landowners in New South Wales, Australia, engaged in participatory design to develop a new online collaboration

tool. Adapting similar approaches for the U.S. context would provide valuable insights into how participants communicate and resolve differing management objectives.

HCI has also done critical work in bringing privacy to the forefront of tool design [49, 173]. Expanding this research in the context of collaborative tools for small landowners could explore new paradigms for data sharing and decision-making. Standley et al. [151], for instance, document how the Kuku-Thaypan media and geospatial data are community driven and controlled. Their data-sharing platform allows only appropriate groups to view sensitive information, giving communities agency over how to store, and who to share data and with whom to share it. Dogan and Wood [56] further highlight the necessity for geospatial data platforms to embody principles of data sovereignty—such as control, access, ownership, and transparency. These paradigms and their impact on perceptions of trust and privacy have yet to be explored with respect to small landowners in wildfire and forest management.

5.3 Developing Tools to Facilitate Decision-Making

We saw in Section 4.2 that many decisions regarding land management practices are often made at the discretion of individual managers, with little decision-making guidance. This discretionary decision-making is largely driven by the significant heterogeneity that managers confront in terms of land characteristics, environmental conditions, and the types of sensors or satellites used, which can result in different land feature estimations and decision outcomes [124]. Although **Decision Support Systems (DSSs)** have a long history of development to address these challenges [105, 165], the adoption of DSSs among land managers remains limited [165]. Future HCI research could develop decision support tools that assist managers by providing information in ways that enhance their ability to make informed and contextually appropriate decisions [111], aspects current tools lack [111].

What Effects Do Composite Indices Have on Decision-Making? One approach to simplifying decision-making is the development of indexes [58]. For instance, Pan et al. [121] created a climate habitability index to condense complex environmental data into a more usable form. A similar index exists for wildfire and forest management. In the U.S., forests and other lands are divided into "firesheds," which are distinct areas delineated according to locations where forests are likely to ignite and spread. Many wildfire and forest management decisions are made and applied at the fireshed level [9] using indices that combine factors such as forest health, biodiversity, water importance, access difficulty, and proximity to human populations [9].

Qualitative HCI methods could explore how decision makers interpret the uncertainty inherent in these composite measures. Moreover, composite indices add another layer of separation between the data and the decision maker viewing the data, which Correll [42] note impacts how the data are consumed. Research should investigate whether aggregating data shifts perceptions or affects the types of decisions made, while also exploring what is lost by implementing this approach [176].

What Ethical Values Are Embedded in Decision Support Technologies? Additionally, future HCI research could focus on raising awareness of the values and ethics underlying current decision-making practices, especially in situations of uncertainty. Are there ethical decisions being made, and if so, how do technologies influence these decisions? In waste management, for example, Comber and Rossitto [40] found that disputes regarding responsible waste care were often ethical, based on historical and contextual meanings as well as the decision makers who managed it. It remains unclear whether similar ethical dimensions, influenced by technology, exist in decision-making within the wildfire and forest management context.

How Do Digital Technologies Define Boundaries between Forest and Non-Forest Land? Furthermore, Coyne [44] explore how digital technologies are influencing the boundaries created between the natural and human-dominated environments. This idea was echoed by our participants, who expressed that the boundaries between forest and non-forest land seemed arbitrary (Section 4.3.2). Simultaneously, they noted that the definitions governing the separation between wildlands vs. peri-urban and rural areas have the potential to exclude communities living in these areas (Section 4.3.2).

Thus, follow-up HCI research could explore how digital technologies shape the definitions and boundaries of "forest" in land management. It could also consider the development of an interactive decision support tool that enables forest managers to define and manage forest boundaries in contested or transitional areas. Such a tool could integrate real-time ecological data, historical land-use patterns, and relevant policy considerations, offering a more holistic approach to boundary management.

5.4 Engaging Local Communities and the Public

Our results further showed that participants are eager to connect with local communities and the public (Section 4.4), but they struggle to incorporate their inputs and opinions (Section 4.4.1). The following sections explore how HCI interventions could help build trust within communities, foster engagement, and support climate resilience.

What Impacts Do Participatory Mapping Practices Have on Local Communities' Understanding of Wildfire Risks and Engagement in Forest Management? Effective wildfire and forest management technologies must be designed with the appropriate end-users in mind, particularly those most exposed to wildfire risks [131]. As P9 emphasized, this requires focusing on the needs and voices of people from local communities. HCI offers valuable tools, particularly through participatory design methods [150] that can engage community members directly in the tool development process.

We argue that participatory climate resilience efforts, such as participatory mapping and cartography, are particularly promising areas of research [103]. Prior research has shown that these methods address many of the challenges identified in our findings in that they (1) enable communities to share local knowledge, (2) build technical capacity, and (3) enhance collective resilience [67, 87, 101]. They also serve as powerful educational tools, helping community members understand complex sociospatial risks like flooding, sea level rise, or wildfire exposure. Participatory mapping methods are especially relevant for rural and hard-to-reach areas, where they have been successfully employed in natural resource management, disaster risk reduction, and rural development across regions like Kenya, South Africa, and Tasmania [78, 101, 155].

There remains a gap in applying these approaches to U.S. wildfire and land management. Efforts in participatory mapping include landscape-values workshops that amplify community perspectives [110], initiatives like the Stewardship Mapping Project, which tracks groups of stewards who care for their natural environments[5], as well as Internet-based public participation GIS methods that map ecosystem benefits experienced by the public [30]. Future work can supplement these efforts and survey land management risks local community members experience.

Moreover, most participatory mapping efforts are limited to single-session workshops [78]. However, continued and sustained knowledge sharing, as well as skill and resilience building, are needed for these interventions to have long-term impacts. Future research could explore how such practices might be extended to sustained, long-term engagements that better support ongoing community needs. Emerging models, such as those combining local mapping with online, open-data

[5]U.S. Department of Agriculture Forest Service. The Stewardship Mapping Project (STEW-Map). Retrieved January 5, 2025 from https://research.fs.usda.gov/projects/stew-map.

repositories in Nepal, offer new opportunities for inclusive, distributed participation [101]. Similarly, Soden et al. [149] ran a month-long workshop engaging interdisciplinary experts in efforts for flood data collection and sharing. What would similar approaches look like for wildfire and forest management? HCI researchers might investigate how participatory mapping, cartographies, and data collection shape understanding and resilience building, both in the short and long terms.

Finally, any participatory effort must grapple with critical issues of data ownership, access, and privacy. It is not sufficient to create participatory maps; researchers must also ask who controls the data and how it is used, ensuring that these systems truly empower the communities they are intended to serve.

What Effects Do Participatory, Multimedia Storytelling Tools Have on Affective Engagement, Environmental Understanding, and Sense of Agency? Participatory mapping tools offer a foundation for engaging communities in knowledge sharing, education, and resilience building, but they can be meaningfully expanded to represent higher-dimensional, affective, and experiential forms of information. For instance, Taylor et al. [155] noted that traditional GIS systems are typically used to document data about the built environment. They enhanced this by incorporating geo-referenced, narrated photographs that reflect participants' personal perspectives and emotional connections to place [155]. This approach highlights a critical question for HCI: how could current modes of data collection be expanded to accommodate alternative, often overlooked methods of knowing and documenting lived experience?

Scholars have long called for HCI to broaden its understanding of technology to include diverse forms of media [94, 151]. Kuznetsov and Tomitsch [94] advocate for documentary filmmaking as a compelling method of capturing and sharing first-hand experiences. With the increasing accessibility of mobile recording tools, communities are now better positioned to produce their own media narratives, creating opportunities for more inclusive and grassroots storytelling. Indeed, documentary filmmaking and other forms of traditionally understudied media have also been used by indigenous tribes to document and share knowledge [151].

HCI's work in visualization and interactive design could further support these documentary and storytelling approaches. Ferreira et al. [61] call for data-humanist methods that contextualize scientific data within narrative frameworks that are relevant to people's everyday experiences. While their work focuses on oceanic climate data, the principle could readily be extended to wildfire and forest management. Interactive installations, for instance, could give voice to local trees, flora, and fauna—personified to narrate the ecological history of fire regimes and the transformations wrought by intensifying wildfires. These installations could prompt emotional engagement, inviting participants to reflect on their responses to—and potential roles in preventing—charred landscapes and disturbed ecosystems.

Storytelling methods, especially those that personify the nonhuman world, can re-center marginalized perspectives and animate abstract concepts. As Ferreira et al. [61] demonstrated through ocean life narratives told from the perspective of whales, such approaches foster emotional resonance and deeper connections to environmental challenges. In the context of wildfire-prone regions, similar storytelling innovations could powerfully support community engagement, cultural continuity, and more inclusive models of environmental resilience. Previous studies have also engaged the public in activities related to birds, animals, or insects. Still, there is potential to extend this focus to forests and trees [51, 93].

Interactive and co-design of games offer similar opportunities to engage communities and experiment with different forms of climate communication. One project [83], for instance, aimed to collaborate with communities at risk of wildfires to design and develop an educational game to enhance resilience and readiness. HCI researchers could expand on visualizations or games

similar to Johns et al.'s game [83] to incorporate and communicate the vastness of the geographic scales involved in wildfire and forest management to the public, along with uncertainties about best management decisions. This could build on prior work showing that data visualization and interactive game design have helped influence individual behavior and the public's understanding of environmental problems [28, 38, 60] to illuminate and address areas of public distrust.

What Are the Experiences, Challenges, and Trust Dynamics of Diverse Community Members Using Wildfire-Specific Crisis Communication Technologies? Engaging local communities in building resilience to wildfires must also involve effective communication during emergencies. While prior research has explored crisis information management for events like hurricanes [142, 148, 175], there remains a notable gap in wildfire-specific communication systems. Research suggests that crisis-specific applications can foster a sense of shared responsibility and increase public trust in local institutions [175]—addressing a challenge uncovered in our interviews. However, significant accessibility challenges have also been documented. For instance, older adults have expressed distrust of crisis apps due to fears of misinformation, scams, and unfamiliarity with digital platforms [175].

These disparities raise urgent questions about wildfire crisis communication. What information do diverse community members need in the midst of a wildfire emergency? How are immigrants and non-English speakers alerted? How are young people engaging with crisis communication platforms, and might they be turning to technology not only for information, but also for emotional support amid climate-related trauma?

A recent example of wildfire crisis communication is the Watch Duty app[6], launched in August 2021 in California. The app aimed to address the absence of timely updates during active fires. Watch Duty crowdsources real-time information from volunteer citizens who aggregate and post updates, often pulled from social media [1]. Since its launch, the app has gained significant traction, with 14 million downloads during the January 2025 Southern California wildfires alone [2]. While it has proven effective in delivering critical wildfire updates, there has been no systematic study of how Watch Duty is actually used on the ground: who relies on it, what usability or accessibility barriers exist, and what forms of trust, tension, or coordination it fosters among users and institutions. Understanding these dynamics is essential to designing more equitable, responsive, and inclusive crisis technologies for wildfire resilience.

Future research could expand the study of disaster response applications and crowdsourced information to also identifying how citizen science applications could be redesigned to effectively communicate the importance and urgency of different actions and responses and at what time intervals these communications should take place. Additionally, future work could investigate strategies for maintaining user engagement, such as integrating educational tools or providing personalized feedback tailored to individual users [130].

Moreover, most citizen science projects beyond crisis and disaster management in urban and developed contexts rely on large distributed populations to collect or analyze data—often via smartphone apps like eBird. However, this model is less applicable in remote areas like forests or during disasters, where access to the Internet may be limited or damage to infrastructure might cut connectivity and power [142]. Researchers could explore how citizen science could be adapted to support wildfire and forest management, such as by enabling users to document damaged or burnt ecosystems offline. New tools could incorporate features like offline file storage and geolocation, enabling users to collect valuable data in areas without Internet connectivity. Comparing these methods with more traditional approaches, such as chatbots, could also help identify innovative ways to improve public engagement in remote forest areas [98].

[6]Sherwood Forestry Service, Inc. Watch Duty. Retrieved June 3, 2025 from https://www.watchduty.org/.

5.5 Bridging Gaps between Computer Science and Wildfire and Forest Management

We found that participants encounter significant technical challenges when using geospatial technologies (Section 4.5), yet they are interested in engaging with computer science beyond these usability barriers. Here, we offer recommendations for how HCI can support bridging these gaps, not only by improving tool accessibility but also by fostering bidirectional learning between forest management experts and computer scientists.

What Are the Usability Patterns in the Workflow of Geospatial Technologies for Wildfire and Forest Management? Prior work in HCI has extensively studied geospatial technologies, consistently identifying usability as a critical barrier to adoption [15, 80, 164, 177]. Ballatore et al. [15] highlight that even participatory GIS methods designed to engage communities in spatial reasoning, data visualization, and decision-making often fail due to usability challenges, leading to abandonment over time. This issue persists even among expert geospatial technology users: a recent study [177] revealed that professionals in earth and climate sciences familiar with tools like Google Earth Engine faced difficulties in mastering geospatial analysis tools. Beyond general usability, research by Henzen [80] calls for tools that help users identify suitable analytical patterns, suggesting that GIS design must better align with users' cognitive workflows. Yet, such patterns have not been documented and identified for geospatial data users in wildfire and forest management. In particular, echoing Ziegler and Chasins [177], we thus argue that geospatial technology research should focus not only on isolated tool interactions and use patterns for that tool but also on the broader analysis pipeline, from data collection to data storage to data analysis.

How Do the Priorities, Motivations, and Collaboration Challenges of Computer Science Researchers Differ from Those of Wildfire and Forest Management Practitioners? Bridging gaps between wildfire and forest managers and computer science experts requires bidirectional engagement; practitioners should collaborate more with researchers, and computer science experts should deepen their understanding of on-the-ground challenges and previous efforts to address those challenges. Translational HCI research has laid important groundwork, documenting tensions that arise when the priorities of domain experts (e.g., wildfire managers) and technologists are misaligned [106]. Our findings echo this pattern: participants reported having sufficient data for decision-making but lacked funding to act on it, highlighting a disconnect between information availability and practical implementation.

Meanwhile, recent CS advances have prioritized larger, higher-resolution models for tasks like forest monitoring [160]. We hypothesize that such a technological focus may not always align with practitioners' immediate needs. To address this, HCI should expand its lens to study computer science research choices and ask: What motivates their tool development? With whom do they collaborate? How do they define priorities, share knowledge, and navigate collaboration challenges? Such investigations could reveal critical discrepancies in how each group perceives local constraints, ultimately fostering more responsive and impactful technologies.

6 Discussion

Previous SHCI studies have addressed domains such as oceans [123], agriculture [100], and climate services [132]. However, we add to this body of work by focusing our investigation on wildfire and forest management, which is crucial for contributing knowledge that aids in sustaining forest ecosystems under future climate conditions [71]. Our focus is specifically on geospatial technologies, where we contribute to an understanding of the technical as well as socio-technical challenges emerging from their use and application for wildfire and forest management.

Our findings reveal that geospatial technologies operate within a complex socio-technical system that involves a range of stakeholders, including academia, public agencies, private landowners,

industry, and local communities (Section 4.1 and Figure 3). Data limitations and knowledge fragmentation (Section 4.2) motivate and color their interactions, as do concerns over the effects of geospatial technology outputs (Section 4.3).

6.1 Considerations for Engaging Local Communities

The burden of wildfires is not evenly distributed. Rural, low-income, Indigenous, and older populations tend to be disproportionately affected due to limited access to evacuation resources, medical infrastructure, and recovery aid [47, 62]. Additionally, undocumented workers or low-wage laborers in agriculture or forestry sectors are often exposed to hazardous smoke without adequate protections [114]. While these vulnerabilities did not arise in our interviews, this absence itself may point to the under-representation of these perspectives in current wildfire management processes, and, by extension, in the development and deployment of geospatial technologies.

We did not interview people from Indigenous tribes or residents of rural communities near forested areas. However, they represent important actors who also manage forest lands or are affected by the management decisions of others, and we wholeheartedly support Soden's [147] recommendation that future HCI research should first focus on those most directly impacted by wildfires or by land management decisions. This includes Indigenous tribes, unhoused individuals seeking refuge on public lands, or those who recreate in forested lands [18], all of whose needs remain insufficiently understood. We call for integrating environmental justice perspectives to ensure that geospatial technologies do not inadvertently exacerbate existing inequalities, but empower communities most at risk.

Particularly when engaging with Indigenous authorities, Dogan and Wood [56] highlight that environmental and geospatial data have been foci of power struggles and contestation, and they are central to ongoing discussions about Indigenous data sovereignty. They document how, despite a Tribe negotiating the removal of certain culturally sensitive data from the state's public portal, some data remain accessible through older Web sites and portals [56]. These instances reflect a lack of trust among Indigenous communities regarding the sharing of local data with governmental agencies or other groups.

Furthermore, Dogan and Wood [56] note that, despite the importance of data sovereignty, there are currently few established protocols for implementing it effectively. We encourage researchers who seek to collaborate with Indigenous authorities to establish clear, culturally sensitive guidelines for the acquisition and use of Indigenous data, ensuring that these practices align with the principles of data sovereignty and community consent.

6.2 Ethical Considerations

While there are exciting opportunities for HCI researchers in wildfire and forest management, we also believe it crucial to keep ethical considerations front-of-mind when developing interventions. There remains a risk that these technologies—and thus HCI research—could contribute to harms and have unintended consequences.

Risk of Misuse and Misrepresentation. Galaz et al. [68] caution that AI and related technologies in forestry may introduce systemic risks. For example, they identify an interpretation bias where farmers treated their land with more (instead of less) nitrogen fertilizer after misinterpreting results from AI-support systems [68, 95].

Moreover, the potential for AI and associated technologies has been generating interest in the forestry market, which is projected to grow from USD 3.9 billion in 2019 to USD 6.1 billion by 2024 [68]. The continued development of "green technologies" in this profit-motivated market could present a risk of greenwashing, i.e., making false or misleading claims about environmental impact [99]. In particular, a screening by the European Commission analyzed green online

claims and found that 42% of them were exaggerated, false, or deceptive [41], while another study showed a 38.31% annual increase in articles at the intersection of AI and greenwashing [112]. Thus, technological developments could undermine, instead of enhance, practices aimed at environmental conservation.

Navigating Interdisciplinary Collaborations. HCI's interdisciplinary nature is a significant asset, but the field has faced criticism for being overly ambitious and presumptuous when tackling new subfields [7, 70]. This can be counterproductive in areas like wildfire and forest management, where many HCI methodologies may already be employed without being explicitly identified [132].

Carbon Footprint of Computing. Additionally, computing itself contributes to the very carbon emissions driving ecological changes in forests [72] through increased demands for energy and non-renewable materials to support facility and computing infrastructure in data centers [3, 4, 54, 85, 178]. Thus, the path forward may lie in embracing the concept of sustainable or even de-growth [97, 139] to realign human impact with the planet's ecological circumstances.

6.3 Limitations

This study's design favors breadth at the cost of depth, and, as with most qualitative research, the findings may not be generalizable to every situation. We may have missed details of challenges that would have been raised by people who perform other functions within public agencies, for instance. The study participants described working with rural communities, small landowners, and Indigenous groups. Yet, these communities were not directly included as interview subjects. Similarly, we did not interview representatives from regional economic development agencies or social scientists focused on rural livelihoods, among others.

As a result, our findings reflect a subset of perspectives from those implementing or supporting wildfire and management strategies, and we lack the direct lived experiences of community members. However, forest management decisions oftentimes affect these on-the-ground communities, and including their perspectives in future work would offer deeper insights into how geospatial technologies intersect with questions of climate resilience and environmental justice. Furthermore, by considering broad technical challenges, we may have missed specific struggles practitioners may have had with a particular tool.

Another limitation is our U.S.-centric perspective. Our participant pool was drawn from the U.S., and largely people who live and work in the Pacific Northwest, which represents a limitation in terms of generalizability. Experiences with geospatial technologies may vary significantly across countries due to differences in policies and available technologies [161]. Additionally, although the U.S. encompasses a wide range of ecotypes, it does not represent every possible ecotype [172]. As a result, other countries may employ location-specific management strategies or have different priorities in choosing management strategies that were beyond the scope of our study [145]. Therefore, focusing solely on the U.S. perspective limits our understanding of the role of HCI in global wildfire management.

7 Conclusion: The Emergent Layer

Today, with the escalation of climate change, forests face unprecedented threats from increased wildfires and pest outbreaks [50], making their conservation more critical than ever. As climate change intensifies and the reliance on technological systems to help mitigate or adapt to the crisis grows, the importance of examining these systems also grows. We believe that our work contributes to this space by improving our understanding of the geospatial technologies forest practitioners use and providing a path forward for future work in this critical area.

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