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Research article

Toward a management framework for smart and sustainable resource management: The case of the Appalachian Trail

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ABSTRACT

With the Appalachian Trail (AT) as our research setting, grounded theory as our methodological approach, and qualitative interviews and archival analysis as our methods, we investigate the role crowdsourced data, social media, and smartphone apps could play in sustainable resource management (SRM). Centering the perspectives of AT resource managers, our analysis reveals that digital technologies can create new challenges and exacerbate existing ones. *Place-centered challenges* intensified by digital technologies are overcrowding and trail infrastructure degradation. *Experience-centered* challenges posed by digital technologies include information overload, limited operational capacity, and tensions between the traditional "AT experience" and digital life. Further, our analysis illuminates the technological, organizational, ethical, and experiential challenges and barriers to the systemic adoption of digital technologies for SRM. These empirical insights result in a management framework that focuses attention on the humanistic and organizational needs of resource managers that could be used for designing and implementing socio-technical systems that better align with social and cultural values of resource management contexts.

1. Introduction

Hiking in the United States surged more than 70% from 2013 to 2022 (Outdoor Foundation, 2022, 2023), even in the face of COVID. Visitor counts on some trails near population centers doubled in 2020–2021 from pre-COVID years as people sought outdoor escapes from pandemic lockdowns (Brassil, 2020; Brown et al., 2021). This spate of trail users has contributed to water quality and habitat degradation by eroding soils, leaving trash, food, and human waste, and expanding existing campsites and creating new ones in the case of overnight backpackers (Ballantyne and Pickering, 2015; Hammitt et al., 2015; Marion et al., 2016, 2020). Such impacts also can significantly degrade the quality of recreational experiences (Lynn and Brown, 2003).

Sustaining the infrastructure to support trail services poses challenges in the face of these deteriorating conservation outcomes and continually increasing use pressures, particularly along popular long-distance trails near population centers (Meadema et al., 2020; Wimpey and Marion, 2010). For example, the iconic Appalachian National Scenic Trail (AT) in the eastern United States, the locus of our research, lies within a day's drive of more than one-half of the US population, and more than 3 million hikers typically experience some part of it annually (Appalachian Trail Conservancy, 2020). The thousands of long distance (LD) hikers who attempt to walk its nearly 2200-mile length in 12 months or less exacerbate trail stresses since the span of time needed for these thru-hikers to traverse the entire trail concentrates most LD hikers in a migrating "bubble" of exceptionally high use (Marion et al., 2020).

In other protected area (PA) natural settings, scientists and managers have piloted the use of smartphone apps and GPS visitor-tracking to protect conservation values by collecting information on visitor numbers and spatial distributions to improve visitor management and reduce resource and social impacts (Muñoz et al., 2020, Stamberger et al., 2018; Meijles et al., 2013; Korpilo et al., 2017; Sisneros-Kidd et al., 2021; Lia et al., 2023; May 2023). Limited work has explored the potential of analyzing crowdsourced data from social media sites to predict visitation in wilderness and backcountry settings and for environmental planning and governance (Ghermandi and Sinclair, 2019; Ghermandi

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et al., 2020; Toivonen et al., 2019; Zhang et al., 2021; Teles da Mota and Pickering, 2020; Wilkins et al., 2021). In the context of the AT, however, proactive, inter-organizational use of digital information and communication technologies to advance sustainable trail and visitor use management practices remains elusive. Moreover, the employment of these technologies can profoundly affect the experience of hikers. Rather than simply employing information and communication technologies for more efficient data collection and discourse, or connecting trail users to natural settings, the use of contemporary mobile applications and platforms are fundamentally transforming the structure and functioning of PA natural settings and people's relationship to them (Stokols et al., 2009; Misra and Stokols, 2012; Graham et al., 2022; Zook and Graham, 2007).

In this paper, we investigate the role crowdsourced data, social media, and smartphone apps could play in addressing sustainable resource management (SRM) challenges on the AT from the perspectives of actors responsible for trail infrastructure (landowners, trail maintainers, resource managers, and club volunteers), something that has not been done before. In doing so, we draw on the literature about hikers' experiences with digital technologies, but we concentrate our efforts on resource managers, by identifying and describing the opportunities and tensions of digital technologies for sustainable resource management of outdoor recreation. Existing work has largely focused on hikers and backpackers. Research on the digital technology practices, orientations, and attitudes of resource managers is scarce. Further, theoeretical frameworks of technological adoption have not adequately addressed the intersections between technological features and psychological, organizational, ethical, and socio-cultural dimensions unique to resource management settings. We focus on addressing these theoretical and empirical gaps by asking the following research questions.

(1) What role might digital information and communication technologies (defined here as smartphone apps, social media, and crowdsourced data) play in supporting SRM?
(2) What are the challenges to digital information and communication technologies playing a larger role in SRM?
(3) What humanistic and organizational issues need to be grappled with to design and implement socio-technical systems for sustainable resource management of outdoor recreation settings?

Our analysis sheds light on the experiential, ethical, organizational, and technological challenges and barriers to the systemic adoption of digital technologies. We use these empirical insights to propose a management framework that focuses attention on these humanistic and organizational needs. We use this framework to present approaches for the design and implementation of socio-technical systems that better align with the social and cultural values of resource management contexts.

1.1. Background

The AT's nearly 2200 miles (3500 km), stretching between Springer Mountain, Georgia and Katahdin, Maine, pass through parts of 14 US states, 8 national forests, 6 national parks, and numerous local jurisdictions (ATC, 2020). It represents an unusual linear feature, a narrow, protected corridor (generally about 1000 feet (300 m) wide), comprising more than 250,000 acres (101,000 ha). Moreover, while it constitutes one of more than 400 units of the National Park System (NPS), the AT is managed through an inter-organizational structure with various federal, state, local, and civil society stakeholder groups. These include the Appalachian Trail Conservancy (ATC), US Forest Service (USFS Wilderness Advisory Group, 2019), the land trust managers, state forests, other land owners, and 31 local trail clubs. The ATC plays a lead role in the trail's protection and maintenance, and its 2021-24 strategic plan has identified strengthening the trail's infrastructure, which includes enhancing its digital infrastructure, as one of its six strategic priorities (https://appalachiantrail.org/our-work/about-us/strategic-plan-2021-2024/). Leveraging digital infrastructure to promote more effective and sustainable use of the trail therefore must rely on coordination and cooperation among these actors, as well as the hikers themselves.

A small literature has emerged specifically on the digital technology practices of hikers and backpackers and the effects of media and communication devices on peoples' experiences with and connection to nature in PA settings (Hyatt et al., 2021; Amerson et al., 2020; Arendt and Matthes, 2016; Levi and Kocher, 1999; Mayer et al., 2009; Pergams and Zaradic, 2008; Armstrong et al., 2022; McCrickard et al., 2018). In addition to their utility for navigation using active GPS tracking and for retrieving other spatial and non-spatial information, digital technologies can allow LD hikers to express themselves via texting, blogging, vlogging, and social media as they find meaning through experiences on the trail. For example, some work has considered how trail cultures manifest on X (formerly Twitter) (Bartolome, 2018), and how thru-hikers can find a sense of community on the trail by maintaining connection to the AT Reddit online community (Kotut et al., 2020).

From the hikers' perspective, the one-to-many communicative aspect of these technologies can allow LD hikers to be a part of a community, even when not formally associated with a place-based club or group. Individuals can communicate bi-directionally with apps, providing information about themselves, their activities, and locations through trackers and sensors and inputting self-reported information, which is aggregated spatio-temporally and presented back to the individual reflexively. Communication can also occur among peers, via sharing of data about performances and experiences using social media functions such as liking and commenting, thus creating networks of LD hikers and enabling new communities of both known and unknown followers coalescing around the practice of long-distance hiking (Barratt, 2017; Groth, 2014; Lomborg and Frandsen, 2016; Smith and Treem, 2017).

A parallel body of research on hiking cultures has provided insights into the diversity of hiking motivations and practices as well as areas of conflict between different hiking identities (Fondren, 2016; Lum et al., 2020). Hikers attempting LD hikes of the entire AT (thru-hikers) have varying motivations and intentions for their journeys (Borrie and Roggenbuck, 2001; Silas et al., 2016), and their technology practices and orientations vary as well (Egger et al., 2020). Some resist the use of technology, welcoming the uncertainty that comes with limited information on the trail, but others embrace it for navigation and its ability to allow them to remain connected to social networks (Rogers and Leung, 2023).

This literature has provided insights into the nexus of digital technology and hiking, but existing work has focused almost exclusively on backpackers; surprisingly little research has appeared on the digital technology orientations, attitudes, and practices of trail maintainers and resource managers and how they see the role of these socio-technological trends influencing their practice. Yet, as noted earlier, scientists and resource managers have begun to use crowdsourced social media data and mobile apps to measure and map visitation in PA settings and understand visitor experiences. For example, Walden-Schreiner et al., 2018 used social media to measure and map visitation hot spots within individual parks. More recent work has focused on using these data to identify distinct types of users (Gosal et al., 2019), parameterize models of visitor flows (Orsi and Geneletti, 2013), and quantify the value of PAs (Sinclair et al., 2018). Social media data also has been used to measure visitor preferences (Clemente et al., 2019; Hausmann et al., 2017; Johnson et al., 2019) and inequitable access to ecosystem services (Martinez-Harms et al., 2018).

Some research has also begun to examine the technological challenges and barriers to the broader applicability and use of crowdsourced data in environmental management, including potential biases in the social media data, data integration and management challenges, lack of quality assurance and pre-processing standards, the absence of ethical codes for handling sensitive information, and doubts about the long-term availability and viability of social media data given changes in

policy and strategy by corporations that own this data (Ghermandi and Sinclair, 2019; Wilkins et al., 2021).

Notwithstanding this small body of work on the use of digital technologies to enhance management of trail infrastructure and visitors, research that has examined the intersections between the organizational, socio-cultural, ethical, psychological, and technological context that undergirds the systematic adoption and deployment of digital technologies in the context of resource management is scarce and warrants more attention (Miller et al., 2020; Valenzuela, 2020). Much remains to be learned about how PA managers and stewards use digital technologies in their everyday work, how they characterize their experiences with digital tools and technologies, including their motivations, attitudes, opportunities, and challenges, and what kinds of tools, information, and resources they find useful in decision-making. We focus on this gap in the remainder of this paper.

1.2. Technology adoption in the public sector

We draw on the extensive theory and empirical research on technology adoption and implementation in public sector organizations to frame our research. Technology, in this body of work, consists of new processes, practices, technologies, products, or paradigms. Prominent studies of technology adoption such as Rogers' (1962) work on diffusion, highlighted characteristics of individuals that influence the pace of adoption, while Davis' (1989) *Technology Acceptance Model (TAM)* emphasized individual level factors such as the ease of use and perceived usefulness of technology as critical factors for technology adoption. More recent theories, such as the *Unified Theory of Acceptance and Use of Technology (UTAUT)* (Venkatesh et al., 2012) integrate several established models of technology adoption to identify key determinants of technology adoption, including performance expectancy, effort expectancy, social influence, and contextual conditions such as the regulatory environment, organizational culture, and leadership and governance. In contrast to the TAM and UTAUT theories, the *Technology-Organization-Environment (TOE) framework* emphasizes the organizational perspective of technology adoption (Tornatzky et al., 1990; Al Hadwer et al., 2021). It postulates that an organization's technological, organizational, and environmental context in combination influences technology adoption processes.

We have learned much from the theoretical and empirical work on the challenges and opportunities of technology adoption in the public sector. Employees may resist adopting new technologies due to fear of job displacement, lack of familiarity, or concerns about the learning curve associated with new systems. In addition, managers and decision-makers are more likely to adopt new technologies if they perceive a relative advantage of the tech-based solution over the conventional technologies and processes and it is compatible with existing processes (Grimmelikhuijsen and Feeney, 2017; Oliveira and Martins, 2011).

With respect to organizational factors, these frameworks emphasize factors such as support from leadership and having a culture of innovation, organizational size, data availability and quality, and organizational structure (Neumann et al., 2023). Further, limited financial and human resources can be a significant barrier to acquiring and implementing new technologies, especially in organizations with budget constraints (Mikalef et al., 2022). If existing systems are outdated or incompatible, this can pose challenges to the integration of new technologies. Legacy systems may require costly upgrades or replacement (Thong, 2001). Adopting new technologies and processes often needs far-reaching structural and cultural changes for public managers and citizens along with significant organizational resources (e.g., skills, training, and quality data). Providing adequate training and ongoing support for individuals has been critical to ensure that they feel confident and competent in using new technologies or technological approaches (Misra et al., 2020a, 2024; Jöhnk et al., 2021; Mergel et al., 2021). Involving key stakeholders in the decision-making process and implementation planning helps garner support and ensures that the technology aligns with organizational goals and individuals' needs.

Missing from these theoretical frameworks, however, are the role of the experiential, psychological, socio-cultural, and ethical factors in technology adoption and their intersections with technological dimensions and organizational conditions unique to the resource management context. The AT's cooperative management structure provides a valuable organizational setting to explore the potential opportunities and challenges of digital technology for SRM. Further, our grounded theory approach elaborates extant frameworks of technology adoption in the public sector by highlighting the interaction between the experiential, ethical, organizational, and technological sub-systems.

2. Method

We used grounded theory (Strauss and Corbin, 1990; Charmaz, 2014) as a methodological approach and qualitative interviews of 18 AT resource managers and trail stewards regarding their use of digital technologies (including crowdsourced data, social media, and smartphone apps), memo writing, and archival analysis as methods in our research.

Grounded theory methodology is an appropriate methodology for our research because existing theories of technology adoption in the public sector do not address the linkages between the experiential, socio-cultural, and ethical dimensions of emerging digital technologies and the unique organizational context of natural resource management settings. Grounded theory provides an approach by which new theories can emerge from data, a goal of our research. To facilitate this kind of theory development, we follow standard practice in grounded theory and refrain from theory-driven interpretations of our data, preferring instead to take evidence at face value. That is, we treat participants as witnesses whose accounts provide useful information about social and psychological processes. One benefit of this methodology is that it does not require us to use a particular theoretical lens through which to read our data. Researchers' conclusions therefore root firmly in the data, ensuring they reflect participants' reality. Further, in grounded theory data collection and analysis take place simultaneously with each part informing the other, which allows us to construct theories of the phenomenon under study. This close relationship between data and findings is a key factor in establishing trustworthiness. Grounded theory provides us with rigorous yet flexible guidelines that begin with openly exploring and analyzing inductive data that lead to the development of theory grounded in data. By applying grounded theory, we can move beyond a simple aggregation of findings and generate a higher-level understanding of the challenges, barriers, and opportunities for utilizing digital technologies in sustainable resource management.

2.1. Sampling strategy

We used a combination of qualitative maximum variation and theoretical sampling (Creswell, 2012; Strauss and Corbin, 1990). Qualitative maximum variation sampling involved selecting managers and maintainers with diverse organizational roles and affiliations, genders, and geographic regions of the AT. This allowed us to gather a variety of perspectives and narratives on the challenges, opportunities, and current uses of digital technology for trail management. Theoretical sampling involved selecting individuals based on their theoretical relevance and novel insights (Strauss and Corbin, 1990; Charmaz, 2014). For our analysis, we employed an iterative process of coding, memo writing, and theoretical and maximum variation sampling until we reached theoretical saturation - a stage in which the analysis and interviews did not present any new data or theoretical insights, as described below in more detail.

2.2. Procedure

Prior to any contact with the participants in our study, we received

our relevant institution's Institutional Review Board approval for recruitment and interview protocols. Subsequently, we contacted regional AT managers for recommendations of appropriate participants who could speak to the potential opportunities and limitations of digital technologies for sustainable trail management. We used the contact list provided to us by the regional managers to reach out to potential participants.

Our interviews were semi-structured and conducted via video conferencing. Each lasted 45–60 min and was video-recorded with permission for note-taking purposes. Each interview was conducted by a lead interviewer. Research assistants took notes and asked follow-up questions as appropriate. All research assistants received training on qualitative interviewing techniques and protocols and received IRB training on human subjects' research protocols. Participants were informed that no personally identifying information would be shared with anyone beyond the project team, and responses would be anonymized.

2.3. Sample

A total of 11 male and 7 female individuals from 10 states participated in our study. The highest number of participants came from Virginia (4), the state that includes the most AT miles (one-quarter of the entire trail). Pennsylvania and Vermont each had two participants, while West Virginia, Maryland, North Carolina, New Hampshire, Maine, and Massachusetts each had one participant. New Jersey and New York shared an interview participant with responsibilities for both states. Our sample did not include representatives from Connecticut, Georgia, and Tennessee because we did not hear back from any managers in these states.

The participants' roles and responsibilities in maintaining and managing the trail varied and included AT club members, ATC regional managers, social media managers from the ATC and clubs, and land managers from Michaux State Forest, Shenandoah National Park, and the George Washington and Jefferson National Forests (Table 1).

Table 1
List of participating land management agencies and trail organizations in our sample.

- **Michaux State Forest**, a State Forest managing AT lands in southcentral Pennsylvania. (https://www.dcnr.pa.gov/StateForests/FindAForest/Michaux/Pages/default.aspx)
- **George Washington & Jefferson National Forests**, a USFS unit managing AT lands in Virginia and West Virginia. (https://www.fs.usda.gov/gwj)
- **AT Clubs**, 31 trail maintenance clubs responsible for most of the day-to-day work of maintaining the AT. (https://appalachiantrail.org/)
  - ***Appalachian Mountain Club***, the oldest US outdoor trail club with 12 chapters throughout the Mid-Atlantic and Northeast. (https://www.outdoors.org/)
  - ***Green Mountain Club***, manages the AT in Vermont. (https://www.greenmountainclub.org/)
  - Virginia Tech**Outdoor Club,** a university outdoor club that manages part of the AT in Virginia.
  - **New York-New Jersey Trail Conference**, a volunteer trail club that manages the AT in New York and New Jersey. (https://www.nynjtc.org/)
  - **Keystone Trails Association**, a Pennsylvania volunteer trail organization. (https://www.kta-hike.org/)
- **Appalachian Trail Conservancy**, the principal organization overseeing the protection and management of the AT. It operates as part of a cooperative management system, working with partners such as the NPS, USFS, state agencies, and 31 volunteer clubs. (https://appalachiantrail.org/)
- **Maine Appalachian Trail Land Trust**, an independent land trust that acquires and protects lands surrounding the AT in Maine for public benefit. (https://matlt.org/)
- **Shenandoah National Park**, a NPS unit managing AT lands in northwestern Virginia. (https://www.nps.gov/shen/index.htm)
- **South Mountain State Park - Maryland DNR**, a State Park that manages AT lands in northcentral Maryland. (https://dnr.maryland.gov/)

2.4. Data coding and analysis

All interviews were video-recorded and transcribed with participants' consent. Within 24 h of each interview, the lead interviewer and research assistants wrote a one-to two-page reflective memo to capture the main ideas, concepts, and questions that emerged from the interviews, including insights stemming from the researcher's interpretation. This was done to help illuminate categories, identify emergent codes, and modify interview questions and prompts as needed.

The interview transcripts, video recordings, and memos were analyzed through an iterative coding approach using a multi-stage process starting with open-coding in the first stage, axial coding in the second stage, and selective/theoretical coding in the third and final stage (Strauss and Corbin, 1990; Charmaz, 2014). Open coding involved a line-by-line coding process to identify initial emerging codes or themes. Axial coding was used to develop more abstract themes by identifying sub-categories. The final step was selective/theoretical coding which was used to further consolidate, relate, and elaborate the themes identified through axial coding.

To ensure the robustness of the data analysis, emerging codes were continuously triangulated with archival resources. This approach involved cross-validating the data from various archival resources to gain comprehensive insights into the organizational and historical context shaping participants' responses. The archival resources included the affiliated organizations' websites, mission statements, and strategic plans such as: (1) The Appalachian National Scenic Trail Resource Management Plan 2008; Reese et al. (2008); (2) ATC Strategic Plan 2021–2024; (3) The AT original vision by Benton MacKaye "A project for an Appalachian Trail" which appeared in the journal of the American Institute of Architects in 1921 (Mackaye, 1921); (4) Websites and Facebook pages of trail volunteer clubs responsible for maintaining sections of the AT; and (5) USFS Wilderness Advisory group reports on visitor use monitoring methods.

3. Analysis and findings

In the sections below, we organize our analysis and findings according to our three research questions.

3.1. Managerial perspectives on the role of digital technologies in supporting SRM

Participants identified four sustainable trail management goals that digital technologies could support: (1) visitor monitoring and management, (2) information dissemination and two-way communication with hikers; (3) trail monitoring and maintenance; and (4) data analytics for decision-making. For each of these goals, we used archival resources and participant insights to develop a set of management objectives. We asked our participants to speak about the digital tools and technologies that have the potential to support or advance each of these goals and associated objectives. Table 2 synthesizes our respondents' perspectives and insights from our archival analysis into a coherent set of proposed goals, strategies, objectives, and associated digital tools to address sustainable AT resource management goals.

3.2. Challenges to digital technologies playing a larger role in SRM

Respondents underscored the significant barriers and challenges to digital technologies playing a larger role in SRM, in contrast to the potential opportunities listed in Table 2. We categorized these challenges into two overarching themes: *place-centered* and *experience-centered challenges*.

Place-centered challenges refer to *spatial or physical trail-related problems* that managers attributed at least partly to social media use by

Table 2
Smart and sustainable trail management goals, strategies and proposed digital tools.

	Sustainable Trail Management Goals			
	Visitor monitoring and management	Information dissemination and two-way communication with hikers	Trail monitoring and maintenance	Data analytics for decision-making
Strategy	Improve data accuracy	Improve inter-organizational coordination and communication with hiking community	Increase responsiveness to real-time information	Leverage data science and data analytics to promote sustainability and visitor experiences
Objectives	Reduce congestion on the trail to: (a) Provide a safe and enjoyable hiking experience; (b) Prevent and contain ecological damage from high visitor traffic; (c) Prevent overcrowding at shelters and campsites and the proliferation of unsustainable campsites.	(a) Disseminate trail-related information (e.g., wildlife and terrain information, best practices for reducing ecological footprint, trail maintenance activities) to hikers; (b) Receive feedback and reports from hikers on trail conditions; (c) Coordinate with stakeholders for trail upkeep.	(a) Collect real-time information on trail conditions; (b) Better inform and engage stakeholders using a common operating platform; (c) Develop a standardized approach for reporting trail conditions that hikers and trail maintainers can use; (d) Develop a standardized approach to monitor problem areas on the trail; (e) Develop a sense of community around trail maintenance.	(a) Develop a digital database with historical data on trail usage, shifting away from paper-based surveys; (b) Develop a standardized methodology to collect data from all collaborating agencies, clubs, and organizations; (c) Develop data analysis strategies for evaluating current practices and policies and decision-making.
Digital Tools	(a) Develop and use digital kiosks as trail counters to automate visitor counts without collecting personal information; (b) Leverage social media to determine the number of visitors; (c) Use a voluntary online pre-hike registration system to collect hikers' information and track visitors; (d) Use websites such as "Where are the hikers" to monitor the hiker bubble, extrapolate information, and guide longer-term planning and decision-making.	(a) Create a standardized digital communication platform across agencies part of the cooperative management system; (b) Create a standardized digital communication tool for volunteer management; (c) Increase direct digital communication channels between hikers and trail maintainers to facilitate trail monitoring and maintenance; (d) Leverage crowdsourced data to enhance trail monitoring and ensure communication to agencies responsible for sections of the trail; (e) Create a digital platform for receiving trail-related information from hikers and providing hikers accurate information about sustainable trail shelters and campsites through apps.	(a) Develop and use digital platforms for responding to hiker reports of trail conditions; (b) Leveraging social media to identify trail violations using the geotagged information; (c) Leveraging apps such as FarOut for standardized mileage reporting to pinpoint problem areas.	(a) Use crowdsourced data to understand hikers' interactions with the trail environment, and their changing needs and wants; (b) Assess hiker behavioral patterns using crowdsourced data to guide communication strategies and policies; (c) Collect and analyze trail-wide volunteer-related information (e.g., number of volunteer hours, types of volunteers, skill sets needed for volunteering) to support trail maintenance.

hikers (e.g., X (formerly Twitter), Instagram, Facebook) – overcrowding and trail infrastructure degradation.

Experience-centered challenges refer to the *organizational, ethical, and psycho-social challenges and tensions* posed by digital technologies more broadly (e.g., smartphone apps, digital photography, texting, and other digital communication, social media) on managers' organizational experiences and their perceptions of hikers' wilderness experience.

3.2.1. Place-centered challenges

3.2.1.1. Overcrowding. "The Appalachian Trail is being loved to death", said one participant. The majority of our participants attributed the place-centered sustainable management challenges to increasing social media use. Recent studies examining the linkages between social media use and overcrowding in national parks and other wilderness settings suggest that viewing Instagram posts and park related information through other social media sites has increased park visitation (Timmons, 2019; Matei, 2020; Sperry, 2018; Doyon, 2020).

> "When I worked in the park, we would do shifts at the visitor centers and people would come up to us and show us a picture on their phone and say, where was this picture taken? I want to go there. This desire to only go to the most popular spots is one of the biggest threats I think, to the resources."

Participants described resource overuse, overcrowding, and high traffic to be particularly problematic in 'instagrammable' spots, such as the Katahdin sign at the northern terminus of the trail and iconic McAfee Knob in Virginia. "Charismatic landmarks", as one participant called them, such as McAfee Knob have witnessed a spike in the number of visitors in recent years reaching up to 600 visitors per day (Taylor, 2023). One participant remarked,

> "… It (social media) feeds user demand because everybody wants to get their picture taken on McAfee … On any day of the week there's going to be … new pictures on McAfee Knob … it feeds demand."

Some managers shared that they use Instagram themselves to plan their hikes and resonated with the appeal of social media to plan, share, and document outdoor experiences.

> I personally love taking photos and sharing and documenting my outdoor excursions … I will plan hikes based on a cool Instagram photo."

This social media driven demand can exacerbate crowding on the trail, which diminishes some people's wilderness experience by reducing the opportunity for solitude (Allen, 2019). Several participants noted their preference for solitude during hiking. Several participants sought the primitive wilderness experience in their own AT hiking experience.

> "I think there's also this very individualistic sentiment to hiking … I'm in the wilderness. I'm here to get away from society and rules and technology and other people …"

> "My biggest thing that I look for is how heavily trafficked the trail is because I don't like crowds."

3.2.1.2. Trail infrastructure degradation. Trail visitation increases, fueled in part by social media that exceed the threshold capacity of trail infrastructure, has amplified the ecological implications of increased foot traffic, such as soil erosion, trail widening, multiple treads, and excessive root exposure (Marion and Leung, 2001), and behavioral issues such as littering and vandalism.

One way to manage and mitigate trail infrastructure damage is to restrict the number of trail users, though recreation ecology research suggests that redistributing use in time and space and improving the sustainability of trail infrastructure are more effective management practices (Marion et al., 2016; Marion et al., 2020). However, a fundamental tension exists between the public land status of the AT and regulating trail use. The distributed governance structure of the AT poses additional management challenges. This tension has existed since the conception of the AT. MacKaye, the person credited with envisioning and articulating the concept of the Appalachian Trail more than a century ago (MacKaye, 1921) promoted decentralized grassroots efforts in governance. In contrast, Myron Avery, an early ATC leader who was responsible for fostering the effort to create and develop the AT, called for more federal involvement. However, the clubs managing and maintaining the AT adopted MacKaye's decentralized approach (Mittlefehldt, 2010). One manager shared:

> "There's been very little effort anywhere along the trail to limit use. There are three places on the trail where there are permits … Great Smoky Mountains National Park, Shenandoah National Park, and Baxter State Park … The only (place) that has insignificant use limitations for a typical overnight person is in the Great Smoky Mountains National Park."

Additionally, several participants expressed concern that social media platforms promote unsustainable and unsafe campsites and campfires. For example, participants reported that crowdsourced information available through mobile apps such as FarOut (previously Guthook), in which hikers share information about sources of water and campsite and shelter locations on the trail, cause infrastructure damage. A study by Rogers and Leung (2023) investigating spatial decision-making via on-site semi-structured interviews, has shown that hikers rely on mobile apps such as FarOut to identify "stealth camping sites," which are not published in guidebooks but are known through word-of-mouth. Sometimes this is acceptable, and even encouraged to help spread out hiker "bubbles", when large numbers of hikers come through a specific trail segment in a short time span. But often hikers camp in illegal or inappropriate locations and share that information through such apps. Other app users, believing this information to be legitimate, camp in the same location resulting in the proliferation of campsites at locations where camping results in negative environmental impacts. App moderators do not always verify the accuracy, appropriateness, and legality of the information posted on their app but they have removed inaccurate and illegal information, particularly when contacted by AT stewards.

3.2.2. Experience-centered challenges

We elaborate, first, on experiential challenges that managers said they face in the context of their organizations in the changing digital landscape. Three thematic concerns emerged from our analysis: (1) Information overload; (2) limited operational capacity; and (3) the need for digital literacy and training.

3.2.2.1. Information overload. Hikers increasingly rely on social media sites such as Reddit and apps such as AllTrails to plan their hikes and seek out and share information during their hikes. These tools provide hikers with advice about what gear to use, water sources, and shelters on the trail (Kotut et al., 2020; Fields, 2017; Saaty et al., 2022). However, public land managers and trail stewards can find it "overwhelming" to monitor and respond to the vast amount of information available online on various social media sites. Participants reported that information overload affects their capacity to monitor problems reported on the trail and to be responsive to hikers' concerns and questions, thus impacting hikers' experiences.

Further, social media was thought to fuel misinformation and disinformation about the trail, which participants found extremely difficult, if not impossible, to correct. For example, two participants expressed their frustration over their inability to control and correct misinformation and disinformation on these platforms.

> "The challenge, as I see it with social media is there are people who are qualified to make statements about how you should behave on the trail because of their experience, because of their training, and so forth. Sometimes they get drowned out by the mass of voices because there are no qualifications needed to get on social media and express your opinion."

> "… and then there's the there's no control over information through social media, which means that you get a lot of junk information. … If the volume of that data is too loud, then it's hard for authoritative, accurate data … and we've seen misinformation spreads a heck of a lot faster than facts."

3.2.2.2. Limited operational capacity. As noted earlier, the AT is governed through a cooperative management system as defined in the Appalachian Trail Comprehensive Plan (National Park Service Appalachian Trail Project Office, 1981). This system is comprised of three main entities: (1) land management agencies that own or manage land parcels through which the AT passes; (2) the ATC, the principal coordinating organization; and (3) trail club volunteers who run the day-to-day operations. A volunteer-based system is seen as crucial for "the soul" of the AT (National Park ServiceAppalachian Trail Project Office, 1981). Each of the 31 affiliated, volunteer-based AT clubs is responsible for managing and maintaining a different section of the AT. These clubs have a range of responsibilities that include trail maintenance, camping management, and building/maintaining shelters. They also assist the ATC and land managers in visitor use and resource monitoring, managing and protecting rare plants and invasive species, and developing management plans (https://appalachiantrail.org/). While this form of governance provides a hands-on, bottom-up approach that creates a sense of responsibility and accountability, it also poses significant operational capacity challenges with the growing demand and proliferation of digital information and communication. AT trail management is highly dependent on volunteer hours and volunteer specialties, as well as the available budget for on-the-ground operations (Cerveny et al., 2022).

The application of digital technology in this context poses a significant problem. Regulating and monitoring crowdsourced information is particularly challenging without dedicated and trained individuals. Several participants reported that they were unable to access various social media platforms to gather, distill, and synthesize information, given limited time and resources and sometimes restrictions on access to some of these sites. Since the clubs rely on volunteers to manage sections of the trail, they do not have the financial or human resources for dedicated staff to filter and respond to social media posts. With reference to the nature of the digital landscape and their limited operational capacity, two participants reported,

> "You have this governance system that's a distributed system of volunteers doing all the work. If someone volunteered to be on Reddit or White Blaze, do you think the club would have the capacity to make sure that's followed through regularly?"

> "… We're adapting, but it's kind of that crawl-walk-run approach … We just don't have the capacity at this point, really that good management plan in place to know how to get the strategies out there."

3.2.2.3. Digital literacy and training. Several participants in our study expressed concerns about integrating technology into their operations, even though they could see the benefits of certain types of digital technologies, such as crowdsourced data for trail management. Some managers reported that forest and park management has traditionally been slow to adopt IT innovations. Others reflected that adopting and implementing new tools and technologies would require managers to step out of their comfort zones and develop new organizational routines and norms. One manager shared,

> "We're always kinda really behind the technological advances in forestry and I think it takes a lot of our staff and others to kind of buy in."

The same participant also emphasized the significance of adapting to the digital landscape.

> "If you get on the train, it's going to make your lives as land managers a lot easier even if it's very uncomfortable, and out of your comfort zone. But if that train leaves the station, I think we're going to be so far behind."

Understanding how technologies can be effectively incorporated into organizations requires an in-depth understanding of the functioning and mission of the organizations. Adopting and implementing new technologies successfully and effectively requires managers to adopt new organizational roles, routines, and structures (Wang and Feeney, 2016). Often there is the problem of technological lock-in, where organizations stick with older and perhaps obsolete technologies and routines because of sunk costs.

> "Some of the things are so new and uncomfortable for some of us—it's like, well, where should we be going with this? If we go down this road and then it stops because something better comes along … but we invested in all this. Where do we go with that? Technological lock-in is a big problem … and the things are changing so fast and becoming obsolete. Yeah, that's where I struggle."

Next, managers reflected on the experience-centered challenges digital technologies pose for what they see as the changing "AT experience." While we did not interview hikers in this research, managers reflected on their perspectives of hikers' experiences, needs, and challenges in the digital environment and how they shape and influence their resource management decisions.

The goal of the ATC's visitor use management program as described by one of the participants *"… isn't just to protect the biophysical aspects of the AT, but it is also to protect the AT experience."* The ATC adheres to MacKaye's original vision and aims to protect the AT experience by providing a setting that is a reprieve from the rapid mechanization of society (Dustin et al., 2017; Acosta, 2019).

> "Social media is a tool, but, if the person is on social media all the time or is on an electronic device all the time, is he experiencing what Benton MacKaye designed the trail to do? What Benton MacKaye designed the trail to be, was a refuge from the over-industrialized society of the 1920s …"

Some participants grappled with the tension between protecting the traditional AT experience that emphasizes self-reliance, minimalism, and developing connection with the land, and the fundamental changes digital technologies have wrought in the structure and functioning of our environments, including natural and wilderness settings. Networked digital technologies such as smartphones make our environments polyfunctional and hybridized (Stokols et al., 2009). With the use of digital technologies, behavioral norms in every setting, including wilderness and backcountry settings can shift people into in a state of constant "polyconsciousness" (Gergen, 2002), where their attention and commitment are divided between multiple spatially and socially dispersed settings (Misra et al., 2016).

At the same time, participants reflected that hikers want and demand conflicting things on the trail.

> "A lot of hikers say they want the disconnection (from technology) … but if we just asked the hikers, what do you want? They would probably say, we want cell phone chargers at every shelter or overnight site … we want a lot of amenities that aren't currently being provided … and that's not our tradition."

3.2.2.4. Heightened predictability. Participants who hiked before the advent of digital technologies recall a distinctly different AT hiking experience. They emphasized the heightened uncertainty they experienced on the trail because they could not anticipate the weather, reach out to friends and family, or learn about trail conditions, among other things that are now possible with smartphone apps. Experiencing the uncertainty and unpredictability of the trail played a crucial role in honing their self-reliance and survival skills. Navigating uncertainty has been described as a critical part of the hiking experience and can be one of the many motivations to embark on a long-distance hike, and evidence suggests some hikers miss it (Driver and Brown, 1986; Rogers and Leung, 2023). Several of our interviewees believed that the pervasive and excessive use of technology can dilute the AT experience by diminishing uncertainty and heightening predictability. To be sure, some of the managers we interviewed reported that they also used smartphones and smartphone apps in a limited way (such as for taking photographs or using maps on the FarOut mobile app) during long distance hikes. Most, however, relied on their compass and paper-based maps and kept their phones out of reach deep in their backpacks.

Managers acknowledged that smartphones have equipped hikers with information to navigate evolving conditions on the trail and anticipate various needs, such as access to weather updates and nearby food sources, allowing many inexperienced hikers to try long distance hiking. However, they emphasized that learning to prepare for the unexpected and survive on the trail is central to the wilderness experience. For example, some of our participants remembered having to carry substantial quantities of food and water to readily adapt to environmental fluctuations. They believed smartphone apps make this type of "over preparation" unnecessary.

> "In general, (the smartphone) removes that sort of common-sense aspect of being in the outdoors. If I'm a serial over packer, I always bring more stuff than I need. And I think that they say your pack is as heavy as your fears, but I feel like I have stuff so that I'm prepared for any eventuality."

It is possible that lowered uncertainty and increased predictability reduces hikers' experience of "flow". A state of flow occurs when an individual is fully immersed in a challenging activity that requires focus on proximal goals in response to unexpected situations (Nakamura and Csikszentmihalyi, 2009). Decades of research in environmental psychology has found that mystery plays a significant role in increasing individuals' experience of the restorative benefits of nature (Kaplan and Kaplan, 1989).

3.2.2.5. Overreliance on technology. Closely related to concerns about diminishing uncertainty on the trail, the participants and the literature pointed to concerns about over-dependence on digital technologies,

sometimes leading to dangerous situations. While the affordances provided by digital technologies can encourage less experienced participants to try long-distance hiking, it can also provide them with a false sense of security because of the lack of data coverage in remote wilderness areas and the need for cell phone batteries to be adequately charged for these devices to function (Hyatt et al., 2021). For this reason, as well as to protect the wilderness experience, some clubs have discouraged their use and deliberately exclude them from lists of essential gear to carry for hiking (Kurczy, 2022). Research in other domains has pointed to declining spatial cognition abilities of individuals and societies because of over-reliance on digital maps, including people's ability to read and understand paper-based maps (Milner, 2016). Consistent with the literature, several participants were concerned about the safety and survival skills of inexperienced hikers who relied solely on smartphones for navigation.

> "The vast majority of people on the trail, whether they're thru-hikers or day hikers, don't know how to use a map or compass and don't carry a map."

Another participant added, *"I think there's some downsides because well, first of all, phones or our technologies can break down. If they break down and if that's the only way that you have to keep track of things, that's someone who can get into trouble."*

Other participants expressed concerns over limited battery life. *"You also may have zero service or zero battery for a lot of your hike. We always tell people to make sure they have a hard copy backup … could be very dangerous without it. I think there's still a place for analog messaging on the trail."* A similar sentiment was shared by another participant, *"If folks are relying on a smartphone while they're hiking the trail, Park Service Rangers always say, please don't do this because inevitably what happens is they don't realize how fast their smartphone sucks through power. Yeah, hey, it's really great that you use FarOut, but pack a map. Print something out like just in case … That's a really hard message to get through."*

3.2.2.6. Experience dilution. The ubiquitous use of social media, the pressures of social comparison that social media creates, and resulting desire for validation has led some park managers to believe that hikers have shifted their focus from being fully immersed in the wilderness experience to prioritizing the documentation of their hiking experience for social media shares, likes, and retweets.

> "It's almost like a checklist to be completed. Hikers are just going from one digital marker to the next. I mean, it's like people that get stuck on terrible roads because their GPS tells them to do that."

While every single participant we interviewed acknowledged the fundamental transformations in human experiences that have occurred in the digital age and the commensurate shifts in the AT experience, there were differing views on the need to preserve the AT experience. Some participants thought that there is a need to accept the different ways in which people engage with the trail, given the reality of hybridization of our everyday settings (Stokols et al., 2009). Others felt strongly that the trail is meant to provide a serene environment to remove oneself from one's routine lives, including digital lives and associated digital stressors. These participants reported consciously limiting their use of digital technologies on the trail. They were critical of certain types of technology use which distract the hikers from being immersed in the trail experience, such as listening to loud music or texting while hiking. These participants' perceptions and feelings are consistent with some research that suggests that excessive use of social media or smartphones displaces time and attention which can dilute the essence of the wilderness experience (Dustin et al., 2019; Vilhelmson et al., 2017).

> "If you're on social media all the time and you're spending all your time keeping track of where you are and ignoring the trees, the animals, the vistas, are you getting the outdoor experience? You're almost having a virtual experience, not a true outdoor experience."

Other research suggests that the use of smartphones supplements and complements traditional methods of developing and maintaining social relationships (Valkenburg and Peter, 2007). One participant, for example, shared with respect to the divergent and nuanced uses of digital technologies on the trail:

> "They also just text each other, and they say - I found this campsite, meet me there … (The trail experience) has changed dramatically in terms of communication primarily, but also communication with the outside world."

Another participant discussed how some hikers use social media to create a hiking community in line with Kotut et al., 2022) study on the role of social media in creating a sense of place-based virtual communities on the trail (Blanchard and Markus, 2002).

4. Toward a management framework for smart and sustainable resource management

A key finding from our grounded theory research is that the purpose and design of current smartphone apps, social media, and crowdsourced data misaligns with some organizational needs for sustainable resource management. This incongruence can intensify or create psychological, behavioral, and ecological challenges. In particular, managerial perspectives on the *place-centered* and *experience-centered* challenges posed by digital technologies combined and cross-validated with our archival analysis revealed a set of humanistic and organizational needs for the design and integration of socio-technical systems for SRM. However, prior theoretical frameworks of technology adoption have not focused on these needs.

While existing technology adoption frameworks tackle user perceptions, organizational factors, and attributes of technology, none of them address *socio-cognitive* factors such as information overload among resource managers, *emotional and experiential* factors such as experience dilution, the challenges of heightened predictability and overreliance on digital technologies in PA settings, and *ethical* factors like access and inclusivity and concerns about hiker surveillance that are important in resource management settings. Yet we know from other technology adoption situations that these factors matter for use and outcomes (Misra et al., 2020a, 2020b, 2024). The dynamic and reciprocal interactions between intrapersonal and organizational factors such as organizational structures and routines, and the characteristics of the technology are also relatively underexplored in current frameworks, and yet the larger technology diffusion literature shows the importance of this interplay for technology implementation and integration (DeSanctis and Poole, 1994).

The management framework for the design and implementation of socio-technical systems for SRM that we propose here emphasizes the relationship between resource managers' values and attitudes, their thinking, the technology, and their work environment. In line with structuration theories of technological change (DeSanctis and Poole, 1994), we find that advanced information technologies such as crowdsourced data, social media, and smartphone apps create new social structures which can enable certain actions and constrain others and generate entirely new patterns of behavior. Further, the interplay between intrapersonal and organizational factors may hold particular importance in the resource management space because end users of technology may resist adoption or shape implementation. Many new technology projects fail or fall short of expectations in part due to bureaucratic processes (Pahlka, 2023). Because the new social structures created by technology must be integrated with existing organizational practices and public values, designing technology with resource managers in mind can increase the likelihood that the technology is adopted at all, and that it serves an organization's goals (Ponce et al., 2016; Wang

and Feeney, 2016; DeSanctis and Poole, 1994).

Employing theoretical coding (Strauss and Corbin, 1990; Charmaz, 2014), we further consolidate and elaborate the aforementioned themes to develop a set of humanistic and organizational challenges and management needs. We categorized these challenges and needs into sub-systems - *technological, organizational, ethical, and experiential,* to develop a grounded management framework for smart and sustainable resource management, which we elaborate below and in Table 3. Fig. 1 provides an organizing graphical framework of the relationship between the various themes and categories that emerged from our analysis.

The *technological sub-system* encompasses data availability, quality, analytics, and integration challenges and needs. The *organizational sub-system* includes the organizational structure, operational capacity, policy tools, and resource constraints and requirements. The *ethical sub-system* is concerned with the alignment between the organization's mission and goals and the design and purpose of digital technologies. The ethical sub-system comprises of concerns about public value, privacy, surveillance, citizen burden, legitimacy, access, inclusion, efficiency, and effectiveness. The *experiential sub-system* concerns the psychological, social, and cultural tensions created or exacerbated by digital technologies. These include information overload, feelings of the lack of agency and autonomy, disconnectedness and disengagement from place-based interactions, and the changing AT experience. In Table 3, we elaborate the challenges under each of these sub-systems using theoretical coding and propose a set of management needs that would need to be addressed for the systemic adoption of digital technologies for SRM. This framework can serve as the foundation of a research program on the design and implementation of socio-technical systems for SRM.

5. Conclusions and discussion

Digital technologies have fundamentally transformed the way many hikers and campers experience wilderness and backcountry environments. They have lowered the barriers to exploring PAs by making information about these settings more open. They have made information and communication more accessible in remote settings. They have enabled many to build online and offline social networks based on shared interests and experiences. For an increasing number of hikers, they have become an integral part of their outdoor experiences. However, this transformative shift has the potential to intensify resource management challenges difficult to reverse, such as overcrowding, resource overuse, and infrastructure. Additionally, digital technologies pose a variety of organizational, ethical, and experiential challenges for resource managers, which prior work on the potential for digital technologies to support and enhance resource management has not considered. Managers and trail stewards raised further concerns about the insidious effects of technological immersion that could further disengage individuals from the outdoor experience and exacerbate information overload and administrative burden.

Using AT resource managers as a case, we present a preliminary framework for smart and sustainable resource management that addresses the interactions between managers' orientations toward digital technologies and the organizational factors that facilitate or constrain effective adoption of crowdsourced data, social media, and smartphone apps in the resource management settings. We find that most digital technologies (smartphone apps, social media, and crowdsourced data) fundamentally misalign with the ethical, organizational, and experiential context of resource management settings. To facilitate the systemic adoption of digital technologies for SRM, the management framework developed here suggests the need for human and community-centered technology design specific to resource managerial contexts. This kind of design process would begin with an approach that considers how potential technologies would function within an organizational, ecological, and cultural setting. Issues of operational capacity, organizational structure, norms and practices, and training needs would

Table 3
A management framework for smart and sustainable resource management.

Sub-systems	Challenges posed by digital technologies for sustainable resource management	Management needs for smart and sustainable resource management
Technological	Quality of crowdsourced data including its representativeness, self-selection and socio-demographic biases, mis- and dis-information, and noise. Inability to integrate multiple sources of online data. Incomplete data on online registration system. Uncertainty about future availability and viability of social media data.	Procedures and protocols for data integration and analysis. Capacity for multi-dimensional analysis for integrating big data with traditional approaches (such as surveys and in person interactions) to mitigate biases in social media data. Standards for pre-processing and cleaning of crowdsourced data. Easy-to-access, international, and open repositories of publicly available data relevant to particular natural resource management issues. Cross-disciplinary collaboration between computer scientists, environmental scientists, and resource managers to address data analytics challenges.
Organizational	Lack of policy tools to translate evidence and analysis into action (e.g., unable to regulate hikers using hiker permits). Limited operational capacity to develop, maintain, and update digital tools and platforms. Increased administrative burden. Lack of access to certain technological tools/sites. Technological lock-in. Lack of training and literacy to implement and use digital tools.	Policy tools to regulate hikers commensurate with the realities of demands for these settings and the ecological degradation caused by overuse. Crowdsourced data analytical approaches as complementary rather than as alternatives to existing approaches. Appropriate training protocols for staff and volunteers to use digital platforms. Collaborations with universities and non-profits to address some of the operational capacity challenges.
Ethical	Need for institutional arrangements with data platforms to gain access to corporate controlled data. Concerns about hiker surveillance and the need to preserve hiker privacy. Burden on hikers to report trail issues. Intrusive technology use on the trail (e.g., distracting notifications on the trail). Concerns about access and inclusivity since not all hikers and trail stewards use smartphones or social media. Tension between preserving unrestricted access to AT as a right to public land and employing regulation/permits to mitigate ecological degradation.	Ethical codes and protocols for handling personal data. Cross-sectoral collaboration for developing regulation and ethics codes and frameworks. Complementary methods and modes of reaching the hiker community without over-reliance on technological approaches to preserve hiker and volunteer agency and autonomy.
Experiential	Limited cognitive capacity to process onslaught of online information because of information overload. Disengagement from place-based interactions on the trail and with broader trail	Human and community-centered technology design that considers implementation processes, including organizational capacity, structures, norms, routines, and practices to

(*continued on next page*)

Table 3 (*continued*)

Sub-systems	Challenges posed by digital technologies for sustainable resource management	Management needs for smart and sustainable resource management
	community. Distancing of hikers from public managers and trail maintainers because of overreliance of digital tools versus in person engagement. Tension between preserving the wilderness experience and adapting to changing values, norms, and behaviors in the digital world.	ensure alignment socio-cultural values. Inclusive and participatory design approaches to design. Platforms and systems that preserve and enhance hiker, manager, and volunteer self-determination, agency, and autonomy. Platforms and systems that understand and preserve divergent values, skills, and trail experiences on the trail.

precede and guide design. The grounded theory management framework developed in this paper can inform a socio-technical information system that aims for a better fit among technological (e.g., data availability, quality, analytics), organizational (e.g., organizational structure, norms, operational capacity, policies), ethical (e.g., public value, privacy, agency, legitimacy), and experiential sub-systems (e.g., values, attitudes, behaviors, motivations, and cognitions) to improve managerial decision-making for SRM.

This framework can broadly apply to a handful of different resource management settings. First, the technological, organizational, ethical, and experiential needs that emerged from this research are broadly applicable to all resource managers (see Table 3 for details). Second, the technological knowledge and training requirements identified by our AT manager sample mirror needs for other types of resource managers. Third, worries about administrative burden and cognitive overload are widely shared resource managerial issues. Fourth, ethical considerations of privacy, security, surveillance, access, and inclusivity are of particular concern for resource managers. Finally, aspects of ecological and recreation outcomes such as preventing overcrowding, resource damage and degradation, and visitor safety are of interest to broad range of resource managers.

Our findings should be considered in light of certain limitations. First, we cannot scientifically generalize from AT managers to the broader class of resource managers and resource settings based on a single study. We can, however, use our study as a test case that could be extended in future work. Future work will need to empirically establish that other resource managers respond in the way that AT managers do in our study. Second, our management framework drew on the perspectives of resource managers and trail stewards because we were interested in the barriers and challenges to systematic digital technology adoption in resource management settings. However, a more complete analysis would include hikers' and campers' uses of digital technologies to better understand how they characterize their experiences with digital tools and technologies, including their motivations, attitudes, opportunities, and challenges. While there are studies of hikers' use of technology in PA settings, this research has not addressed the potentially divergent values and experiences of the hiker community as compared to resource managers and their implications for resource management. This type of analysis would add depth to the management framework presented here. Third, our study is limited by the AT managers who responded to our request for an interview. Our sample did not include representatives from three of the 14 US states through which the AT passes. While the use of theoretical sampling (where the process of data collection is controlled by the emerging theory) and the use of archival resources to triangulate the data partly address some of these limitations, it is possible that our findings would be more robust if we included participants from each of the 14 AT states. Fourth, our interviews were video conference-based. A stronger research design would involve spending longer periods time with AT managers, trail stewards, and volunteers in their field and organizational settings providing a more in depth understanding of their digital technology experiences and behaviors. An important next step for this research is to study the perspectives and experiences of managers and hikers in other PA settings to generate a more broadly generalizable management framework for smart and sustainable resource management.

Limitations notwithstanding, we believe our framework has implications for both future practice and research. Resource managers who

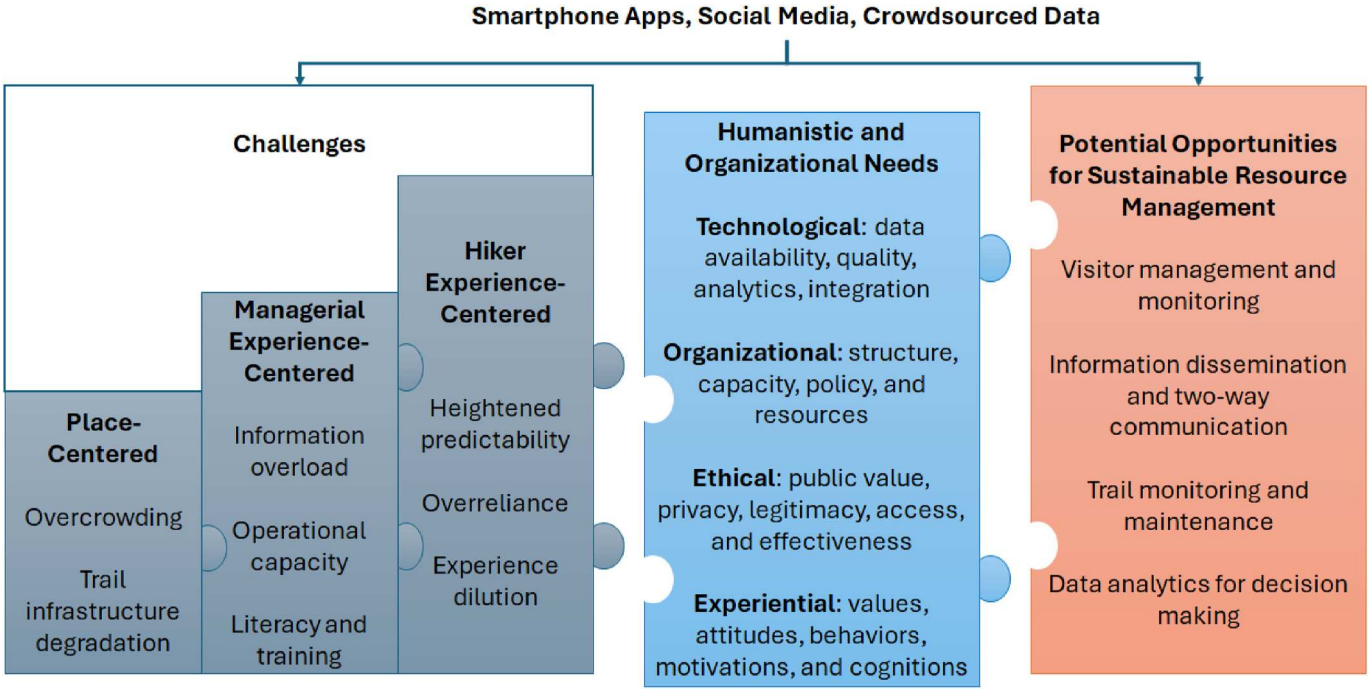

Fig. 1. Misalignment between humanistic and organizational needs for SRM and current digital technologies and resultant place-centered and experience-centered challenges.

wish to implement the framework can rethink their program when adopting digital systems such as smartphone apps for tracking and communicating with hikers. In particular, they should consider the management needs we outline in Table 3. For example, resource managers should budget for and implement appropriate training protocols for staff and volunteers before using digital platforms. Further, resource managers should consider whether they have standards, procedures, and protocols in place for pre-processing and cleaning of crowdsourced data and integrating data with traditional approaches (such as surveys and in person interactions) to mitigate biases in social media data. Cross-disciplinary and cross-sectoral collaboration between computer scientists, environmental scientists, and resource managers can address some of these data analytics challenges.

For scholars, our smart and sustainable resource management framework results in a number of research questions and hypotheses that could be examined in other types of study designs. For example, how might inclusive and participatory technology design processes integrate knowledge of implementation processes, including organizational structures? How might we design platforms and systems that preserve and enhance hiker, manager, and volunteer self-determination, agency, and autonomy? How might we design platforms and systems that understand and preserve divergent values, skills, and trail experiences on the trail? What ethical codes and protocols needed to be developed for handling personal data in resource management settings? What kinds of data integration and analytical approaches can mitigate biases in social media data?

Our research examines the intersections between the organizational, socio-cultural, ethical, psychological, and technological context that undergirds the systematic adoption and deployment of these technologies in the context of resource management. This study is a first step in gathering empirical data on PA and resource managers' perspectives about digital technologies, including their motivations, attitudes, opportunities, and challenges, and what kinds of tools, information, and resources they find useful in decision-making. The resulting framework outlines the managerial, organizational, and technological needs that will need to be addressed to align digital technologies with desired socio-cultural and ecological outcomes. This information is foundational to the responsible design, development, and deployment of socio-technical systems in resource management contexts.

CRediT authorship contribution statement

Shalini Misra: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Norhan Abdelgawad:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Kris Wernstedt:** Writing – review & editing, Project administration, Funding acquisition. **Morva Saaty:** Investigation, Data curation. **Jaitun Patel:** Investigation, Data curation. **Jeffrey Marion:** Writing – review & editing, Investigation. **Scott McCrickard:** Writing – review & editing, Supervision, Funding acquisition.

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Data availability

The data that has been used is confidential.

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