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Digital strategies in wildfire management: social media analytics and Web 3.0 integration

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Received: 12 December 2023 / Accepted: 6 May 2024
Published online: 15 May 2024

Abstract
This study proposes the integration of specific social media analytics (SMA) metrics into existing U.S. wildfire management systems to enhance their ability to accurately predict, monitor, and respond to wildfires in a timely manner. In addition, the examination of SMA's influence on shaping wildfire-related policies is addressed in our analysis with respect to the mitigation of the extent and effects of such disasters. Furthermore, the potential of Web 3.0 technologies in achieving these objectives is analyzed as part of this work. The results highlight that advaa analytics (SMA) metrics to wildfire management and along with Web 3.0 integration.

Keywords Wildfire management · Social media analytics metrics · Web 3.0 · Policymaking

1 Introduction

The rise in wildfire frequency and severity that has swept the United States, particularly since the nineteenth century, is one of the great environmental and safety concerns of present times. The recent research from Cartier [1] has showcased this surge with significant impacts in the western states and the Great Plains. In response to this upward trend, the modern U.S. wildfire management system is evolving with advanced technologies. For example, current U.S. wildfire management systems widely use terrestrial and aerial systems to collect wildfire data [2]. Terrestrial systems are based on Information and Communications Technology (ICT) and advanced camera technologies, but they are often limited by coverage constraints. Aerial systems give broad coverage, but their effectiveness is hindered in certain conditions of visibility. Recognizing these limitations, wildfire management agencies have evolved beyond traditional terrestrial and aerial systems. Furthermore, the concept of 'human sensors' was introduced to the modern U.S. wildfire management system in the recent decade, leveraging firsthand information from cameras and insights provided by firefighters and other on-site responders [2]. This human-centric approach enhances situational awareness and complements the data collected through technological systems, creating a more robust and responsive wildfire management system. Transitioning from this human-centric perspective, emergency management has further evolved with the emergence of social media. Unlike the limited scope of terrestrial and aerial systems, social media platforms, such as Facebook and Twitter (now known as X), have grown to become an integral part of emergency communication strategies. Such platforms offer novel ways for agencies to disseminate information and engage with the public [3]. However, the adoption of social media in emergency management faces barriers to effectively using social media. For example, Plotnick and

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Hiltz [4] highlighted several significant challenges that impede the use of social media by U.S. emergency management agencies. These include limited adoption rates, staffing constraints, the absence of formal policies or guidelines, skills and training deficiencies, concerns over trustworthiness and information overload, and system-related issues. Given theseobstacles, various SMA techniques have been developed to mitigate them. For instance, Vaghani [5] presented an SMA technique called CrowdCorrect, which enables analysts to cleanse and curate social data effectively, preparing it for reliable analytics. This research also highlighted SMA as an emerging approach with great potential to offer foresight into future occurrences.

It is also important to note that the economic implications of slower wildfire response times are significant, with research indicating that even modest improvements in response times can lead to substantial reductions in the frequency of large uncontained wildfires. The Western Forestry Leadership Coalition's report [6] highlighted that delayed response is associated with exacerbation of the scale and severity of wildfires using the 2018 wildfire season in California as a case study. Similarly, research funded by the Moore Foundation [7] provided a direct estimate that a 15-min reduction in average response times could reduce the frequency of large uncontained wildfires by three to seven percent, translating to $3.5–$8.2 billion in economic benefits and $150–$350 million in fiscal benefits in California. Although wildfires are not inherently unpredictable, current wildfire management systems lack the capability to forecast them in a timely manner. This gap in predictability and the risks associated with delayed responses can lead to significant losses. Our research focuses on identifying the advantage of applying SMA metrics to wildfire management. We also design a series of conceptual SMA metrics that leverage the strengths of SMA for faster response in managing wildfires. We suggest embedding these metrics into a dashboard system within the existing U.S. wildfire management systems. This proposed integration is designed to augment the systems' predictive accuracy, monitoring, and response capabilities in managing wildfires.

1.1 Research questions

Our study focuses on the identification and development of customized SMA metrics for U.S. wildfire management systems to improve wildfire response efforts as well as its link to Web 3.0. It explores two main questions:

1. What unique SMA metrics can be incorporated into the U.S. wildfire management systems to enhance the speed and accuracy of response efforts?
2. How could Web 3.0 technologies further enhance SMA and its integration into wildfire management systems?

1.2 Contribution

Our study develops tailored SMA metrics for enhancing U.S. wildfire management systems. These metrics focus on improving the response times in U.S. wildfire management systems. By integrating these SMA metrics into a conceptual dashboard, we demonstrate a methodology that could streamline timely interventions. Furthermore, we discuss the potential of Web 3.0 technologies, specifically how they support and amplify the application of SMA in wildfire management. Concentrating on technologies that directly enhance SMA, such as blockchain and the Internet of Things (IoT), we highlight their role in strengthening the integration of SMA into wildfire management efforts.

1.3 Organization

The rest of this work is structured as follows: Sect. 2 reviews relevant literature, setting the stage for our research. Section 3 describes our methodology. Section 4 details the proposed SMA metrics and the development of a real-time dashboard that integrates these metrics. Section 5 explores the application of these SMA metrics to the WildfireSAFE platform, demonstrating the advantage of integrating them into existing U.S. wildfire management systems. Section 6 offers an evidence-based analysis that highlights the operational improvements achieved by integrating SMA into emergency management. Section 7 discusses how Web 3.0 technologies could enhance SMA applications in wildfire management, highlighting their supportive role in amplifying SMA's advantage in wildfire management. The conclusion in Sect. 8 summarizes our findings and suggests directions for future research while highlighting both academic and practical implications.

2 Related literature review

The integration of SMA in wildfire management and policymaking is a multifaceted domain that intertwines technology, emergency response, and governance. This literature review addresses the evolving role of SMA in policy contexts and its application and advantage in managing wildfires. Our work falls within four literature streams: SMA in the public governance, social media in emergency and wildfire management, the shift from Web 2.0 to Web 3.0, and development of SMA techniques in emergency management. Indeed, social media data has been adopted within the Fire and Rescue Services (FRS) worldwide, especially since 2011, for emergencies and wildfire management (WFM). Furthermore, earlier research has developed theories and models on using social media data for combating misinformation and improving the efficiency of data mining in development of SMA applications. Mendoza et al. [8] proposed the use of supervised learning to classify social media content into emergency and non-emergency categories, demonstrating the potential of social media as a real-time emergency detection tool. Similarly, Huang et al. [9] developed an integrated approach using BERT-Att-BiLSTM for detecting emergency-related posts and extracting essential attributes (what, where, when) for early emergency event detection. That said, past research has contributed to three key areas: the inherent value of social media data, the types of value-added information available on social media platforms, and the development of Social Media Analytics (SMA) techniques for emergency management. Building on this foundation, our paper suggests using specified SMA metrics and advanced visualization systems to leverage past research findings with particularly focus on reducing response time during wildfires. Meanwhile, Web 3.0, often referred to as the third generation of the Internet, marks a shift towards decentralized digital networks underpinned by advanced technologies like blockchain and semantic web. In contrast to Web 2.0's focus on user collaboration and interactivity, Web 3.0 emphasizes enhanced data privacy, security, and user empowerment through decentralization [10]. Our paper considers this technological leap presents a considerable opportunity for government agencies to enhance SMA applications in wildfire management. To this end, our paper further investigated contemporary research and practical deployments surrounding Web 3.0 and its associated technologies. This investigation highlights the potential synergies between Web 3.0 innovations and wildfire management as well as showcases how these synergies can amplify the use of SMA metrics in improving responses to wildfires.

In public governance, SMA is increasingly recognized as an effective method for uncovering key insights, essential in shaping evidence-based policymaking systems. This segment of the literature review is dedicated to exploring the broad application and impact of SMA in policymaking. Research indicates a steady incorporation of social media in government functions [11], serving various roles from disseminating information to the public [12] to supporting decision-making in situations that need fast response [13]. However, challenges such as technical and organizational barriers [14] and issues related to privacy and accountability [15] are evident. Specifically, there is an observed research gap in the context of wildfire management. General emergency management benefits from social media's immediate and wide-reaching capabilities, but wildfire situations, characterized by their urgent and unpredictable nature. Our research points to a need for strategies specifically tailored to wildfire scenarios. These strategies should be capable of addressing the necessity for real-time data and sensor undetectable features of wildfire situations, thereby improving the timeliness of policy responses in wildfire context.

The literature on the development and adoption of social media within emergency and wildfire management grew slowly before 2011 but steadily increased in the recent decade. Latonero and Shklovski [16] identified several barriers to the effective use of social media in emergency management, focusing on organizational resistance to adopting new technologies and the need for training to navigate the vast, unstructured data of social media platforms. The study recommended fostering a culture of innovation within emergency management organizations, promoting the role of information evangelists who can champion the use of social media, and developing strategies to overcome technological challenges. Wang, Ye, and Tsou [17] made a step forward to demonstrate how Twitter activities provide valuable insights into wildfire characteristics across spatial and temporal dimensions, advocating for the integration of social media data to elevate emergency situational awareness. Furthermore, the study by Reuter, Ludwig, Kaufhold, and Spielhofer [18] revealed insights from emergency professionals on social media use during emergency response, emphasizing the need for prioritizing and categorizing social media data to manage information overload and concerns about the reliability of information amidst rumors. The study also concluded social media is an effective tool for enhancing situational awareness, albeit with risks associated with misinformation. Our study leverages these findings, specifically targeting SMA optimization in wildfire management, thoughtfully balancing the identified benefits and risks of social media usage. Similarly, Fosso Wamba, S., Edwards, A., & Akter, S. [19] highlighted the

transformative impact of social media on emergency operations, specifically through its rapid information sharing, public engagement, and situational awareness capabilities. The emphasis is on how these platforms facilitate a two-way communication channel between emergency services and the public, offering a direct line for real-time updates and feedback. Recently, Fromm et al. [20] analyzed a specific scenario of improving decision-making in emergency control rooms by integrating vast social media data. They introduced a method to visualize relevant information from social media platforms via Augmented Reality to support informed emergency responses. This approach offered a tailored solution for managing the large volume of social media data for wildfire responders. These studies collectively highlight the shift towards the adoption and development of social media platforms for disaster awareness, information dissemination, and public engagement during crises. Our work addresses specific gaps in U.S. wildfire management, such as the advantage of social media as an alternative data source for wildfire response, and the development of new SMA metrics for existing wildfire management systems.

The progression from Web 2.0 to Web 3.0 sparks a potential shift in Internet technology, bearing various implications for the use of SMA in wildfire management. On the one hand, Web 2.0 laid the groundwork for enhanced social engagement online [21]. However, it also raised concerns over data privacy and centralization of control, with a few entities dominating the web [10]. On the other hand, Web 3.0's decentralization paradigm redistributes power, fostering a more equitable digital environment [10]. This emerging technology framework leverages blockchain and semantic web advancements, promising a more equitable distribution of internet control and a heightened emphasis on personalization and security [10]. This shift presents governments with novel opportunities to leverage SMA to craft informed, responsive strategies for wildfire management. However, a notable gap persists in current research, where the focus of Web 3.0 has predominantly been on developing a more robust technological framework, with limited exploration into their synergies between Web3.0 and SMA for managing wildfire. Our research bridges this gap by connecting distinctive characteristics of Web 3.0 to enhance SMA and its integration into wildfire management systems.

The burgeoning field of research on the development and integration of standardized and automated SMA tools in emergency management highlights the significant role SMA plays in enhancing the social media data use during crises. Nieuwenhuijse, A., Bakker, J., & Pechenizkiy, M. presented [22] a framework designed to filter and classify data from platforms like Twitter to isolate information pertinent to ongoing or potential emergencies. This approach helps in aggregating critical insights from vast amounts of unstructured data, demonstrating the potential of social media as a real-time sensor network for emergency management and response teams. Later, Jing Lin (2022) discussed how multimodal social media information can enhance emergency management through early warning, monitoring, and control. The study proposed a comprehensive SMA framework for processing this information, including methods for obtaining, integrating, mining, and evaluating social media content to support emergency responses. Yet, there are also studies point out the challenges faced by SMA implementation in emergency response. The challenges include standardizing measurements across diverse platforms and the complexities involved in the deployment of these tools in dynamic, unpredictable emergency scenarios [23]. Furthermore, the literature reveals a lack of comprehensive methodologies that can seamlessly incorporate cutting-edge technologies like AI and IoT, which are poetical accelerators for SMA applications in disaster risk management [24, 25]. The results of our study suggest the advantage of integrating tailored SMA metrics into current wildfire management systems. This endeavor acts as an initial measure, stimulating subsequent advancement of scalable wildfire management systems and tools that use SMA, with the aim of achieving wider implementation.

3 Methodology

In this section, we outline our methodology for developing our proposed SMA metrics by applying an indexing method. This approach leverages the highlighted advantages of social media data in disaster management found in previous studies, such as using social media as a real-time sensor network to gather critical insights for emergency management and response teams. Specifically, we aim to aggregate information to capture early warnings, monitor, and control situations, as well as facilitate rapid information sharing to support decision-making in scenarios requiring swift responses. These comprehensive SMA metrics are then integrated into a real-time dashboard, designed to complement and enhance existing wildfire management systems. Notably, our methods are applicable to any social media platform that may be accessed programmatically, but we mainly use Twitter (now known as X) for illustration purpose in the paper. Meanwhile, we suggest collecting textual data from social media platforms for building SMA metrics and the dashboard. We intentionally exclude non-textual data like audio, images, and videos. Although this non-textual information could provide valuable insights, the computational cost and analysis time might not necessarily improve response times. Furthermore,

the requirement for government agencies to use advanced tools for non-textual data analysis could lead to more barriers to adoption. Specifically, our methodology would use a Python-based scraper to gather textual data from social media APIs related to specific wildfire incidents. The targeted social media posts should include the wildfire's name, user location, date of the post, and content. The wildfire name can be identified through custom keywords and hashtags, utilizing names from official wildfire records, media reports, or a combination of the region's name with "wildfire" for broader searches. To ensure the relevance and quality of the data collected, we will apply validation techniques such as the Bag-of-Words Language Model (BoW) and Latent Dirichlet Allocation (LDA) for topic modeling. In the dashboard system we've designed, the displayed data will be categorized into non-seasonal adjusted and seasonal adjusted types. Initially, non-seasonal adjusted data will be published, derived directly from our specified social media data mining mechanism. Seasonal adjusted data, on the other hand, will undergo a cross-referencing check with data from government reports to correct any potential errors or outdated information. For instance, we can easily download official wildfire reports from the National Interagency Coordination Center (NICC). These reports offer detailed accounts of wildfire incidents. Given that these reports are usually available in PDF format, we suggest converting these PDF documents into CSV format utilizing Python. This conversion facilitates a more streamlined process for ongoing cross-referencing checks. If budget permits, we recommend a manual review mechanism as part of the overall methodology where experts periodically scrutinize the data for anomalies or inconsistencies. This dual-layer verification strategy is designed to reduce the risk of disseminating misinformation.

In constructing SMA metrics, we propose indices to evaluate social sentiment and engagement regarding wildfires. This process involves the development of the Wildfire Social Sentiment Index (WSS), which is further divided into the Wildfire Social Popularity (WSP) index and the Wildfire Social Threats (WST) index. These metrics are designed to measure both the visibility and perceived severity of wildfires on social media platforms. Following this, the methodology involves planning the creation of a real-time social media analytical dashboard that incorporates these SMA metrics. This dashboard would be designed as an innovative tool for the ongoing monitoring and interpretation of social media data during wildfire incidents, integrating a range of analytical capabilities. Among these features are:

- Awareness Module: This module is designed to measure public awareness and engagement with wildfires on social media. It incorporates our conceptual SMA metrics, to provide insights into how widely discussed and engaged with wildfire topics are on social platforms.
- Geographic Module: This component aims to map social media posts interactively, offering additional geographic and demographic insights. By visualizing social media posts on a map, stakeholders can quickly identify areas of high concern or engagement, facilitating targeted response efforts.
- Resources Module: Acting as an online emergency support hub, this module enhances the flow of information among all relevant parties involved in wildfire management. It aims to centralize and streamline communication, ensuring timely and effective dissemination of crucial information during wildfire events.

These features of the dashboard showcase how to leverage the advantage of applying SMA in wildfire management to enhance response efforts.

4 Construction of SMA metrics and analytical dashboard (conceptual)

In this section, we detail the construction of our proposed SMA metrics and our conceptual analytical dashboard. We outline the calculation methods for the SMA metrics, illustrating how each module of our designed dashboard incorporates specific metrics. Through examples, we demonstrate the functionality and appearance of each module. Despite the conceptual nature of this work, our structured design process, detailed formulas, and concrete examples aim to vividly showcase how our approach leverages the identified advantages of SMA in previous studies. Specifically, we focus on enhancing the timeliness of responses in wildfire management, illustrating the potential of our conceptual work to improve emergency response through strategically applying our designed SMA metrics to wildfire management systems.

4.1 Wildfire Social Sentiment Index (WSS) construction

In our proposed SMA metrics, we conceptualize the Wildfire Social Sentiment Index (WSS) to gauge public sentiment regarding wildfires through social media analysis. The WSS is designed to be a composite measure, combining two distinct

indices: the Wildfire Social Popularity (WSP) Index and the Wildfire Social Threats (WST) Index. It is worth noting that we do not explicitly make a distinction between social media posts providing information and discussing information. Instead, combining the WST and WSP Indexes allows us to implicitly gauge the distinction between the overall situation about informational and discussion-oriented posts, as posts providing information tend to have neutral sentiments, and wildfires with only official government posts would have lower engagement. Meanwhile, posts that are "spam" in nature and merely use the name of a given fire to draw attention to content not directly related to the fire are assumed to be filtered out and are not counted in our seasonal adjustments process.

The WSP Index aims to quantify the level of public engagement with wildfires on social media. It is calculated by counting posts containing specific phrases and hashtags related to wildfires. The metric involves comparing the volume of wildfire-related posts in a specific region against statewide and nationwide post volumes. We determine the WSP Index by dividing the ratio of regional to statewide post volumes by the ratio of statewide to nationwide post volumes, then multiplying the quotient by 100. Conversely, the WST Index is focused on assessing the perceived severity and impact of wildfires as reflected in social media sentiment. This index utilizes sentiment analysis techniques on social media posts discussing wildfire-related damages, emotions, and rescue efforts. We propose to fine-tune the BERT model using both auto-labeled and human-labeled disaster sentiment datasets, improving its ability to interpret the nuances of social media language during wildfire events. Following this, we will apply topic modeling techniques like LDA to extract and interpret the dominant themes in these conversations. The Index is then calculated by comparing the average sentiment score of regional wildfire-related posts against the national average, multiplied by 100. The formula for the WSP Index is as:

$$\text{WSP Index} = \frac{\text{Regional Post Volume} \times \text{Nationalwide Post Volume}}{\textit{Statewide Post Volume}^2} \times 100$$

$$\text{WST Index} = \frac{\text{Sentiment Score of Regional Posts}}{\text{Sentiment Score of National Posts}} \times 100$$

In constructing the WSS Index, we give differential weighting to the WSP and WST indices. The WST Index, which captures public sentiment regarding the severity of wildfires, is given a higher weight (70%) due to its critical role in influencing public response and informing policy decisions. The WSP Index, representing social engagement, is assigned a weight of 30%. The design of the WSS Index also reflects several research findings. For example, Huang et al. [9] suggest that visual analytics techniques combined with social media sentiment modeling can uncover valuable insights in disaster scenarios. Similarly, the Kryvasheyeu et al. [26] study demonstrates a correlation between social media activity and disaster damage, facilitating rapid assessment. The final WSS is computed by amalgamating these weighted components: 30% of the WSP Index plus 70% of the WST Index. The entire WSS calculation formula is as:

$$\text{WSS Index} = (0.3 \times \text{WSP Index} + 0.7 \times \text{WST Index})$$

4.2 The design of a real-time social media analytical dashboard

In this section, we outline the development of a real-time social media analytical dashboard, intended as a ready-to-use tool to enhance understanding and response to wildfires using data from social media platforms. This conceptual SMA metrics integrated dashboard provides a structured approach to gathering and interpreting social media data related to wildfire incidents.

4.2.1 Awareness module

This segment of the dashboard would focus on gauging public awareness and engagement with wildfires through social media. It includes metrics like Wildfire Social Media Volume (WSMV), which counts posts containing wildfire-related keywords in a specified region and timeframe. The Wildfire Hashtag Cloud (WHC) tracks and displays the frequency of specific wildfire-related hashtags, offering insight into trending discussions. The Wildfire Influencer Impact Score (WIIS) measures the impact of influential social media users on wildfire discourse, and the Wildfire Engagement Rate (WER) calculates the average engagement with wildfire-related posts. Detailed information about the awareness metrics can be found in Table 1.

Table 1 Details of Awareness Metrics

Metric name	Description	Examples
Wildfire Social Media Volume (WSMV)	Count the number of posts containing specific wildfire-related keywords (e.g., #wildfire, #firealert, #evacuation) within a specific geographical area and time frame	# of wildfire-related tweets/d # of wildfire-related tweets/m # of wildfire-related tweets/y average # of wildfire-related tweets/d average # of wildfire-related tweets/m average # of wildfire-related tweets/y
Wildfire Hashtag Cloud (WHC)	Track the frequency and spread of specific hashtags related to wildfires (e.g., #wildfireprevention, #wildfirerecovery)	tag cloud heatmap
Wildfire Influencer Impact Score (WIIS)	Identify users with a high number of followers (e.g., over 10,000) who are actively posting about wildfires. Measure their engagement (likes, retweets, comments per post) to assess their influence	$\frac{\#\text{of wildfire-related posts} \times \text{Average engagement per post}}{\text{Total \# of followers}}$
Wildfire Engagement Rate (WER)	Calculate the average number of retweets and shares for posts containing wildfire-related keywords. High numbers could indicate a wider reach and greater public engagement	$\frac{\text{Total Engagements on Wildfire-Related Posts}}{\text{Total Wildfire-Related Posts}}$

4.2.2 Geographic module

This module would be designed to integrate the geographic data of tweets with wildfire occurrences. It would tag posts on an interactive map, providing additional geographic and demographic data. This approach leverages the concept "crisis mapping" to not only map wildfires but also to connect them with the social media landscape, offering a more comprehensive understanding of the impact and reach of these events. Previous research has demonstrated the effectiveness of the "crisis mapping" approach in generating accurate maps to guide and prioritize rescue efforts during disasters. For instance, Middleton et al. [27] compared tweet crisis maps to official post-event assessments to demonstrate the accuracy of social media for crisis mapping and disaster management. Figure 1 demonstrates a demo of the geographic module for California in 2017 and 2018.

4.2.3 Resources module

The resources module would serve as an online emergency support center to facilitate the flow of information among all corresponding parties. This module is interactive and allows for two-way information sharing. Users can seek assistance in wildfire rescue and relief operations in their region of interest using pre-trained AI or by consulting with experts. Social network groups of volunteers or experts from various fields can post wildfire-related advice and provide ongoing updates on wildfires in the region. Additionally, the resources module would provide a summary of local fire management resources available to users. This includes the profiles of volunteers, experts, and official responders, which contain information about their location, skills, resources, and statistics such as the number of available volunteers, average response time in the past, and the preparedness level of official responders.

5 A potential application of the proposed SMA metrics for the WildfireSAFE platform

The Federal Wildland Fire Management System (FWFMS) in the United States is a three-tiered system that coordinates efforts between federal, state, and local agencies to manage wildfires in the country. The purpose of the FWFMS is to provide a comprehensive framework for managing wildland fires on federal lands [28]. The system is led by five federal agencies, including the USDA's Forest Service, the Department of the Interior's Bureau of Indian Affairs, the Bureau of

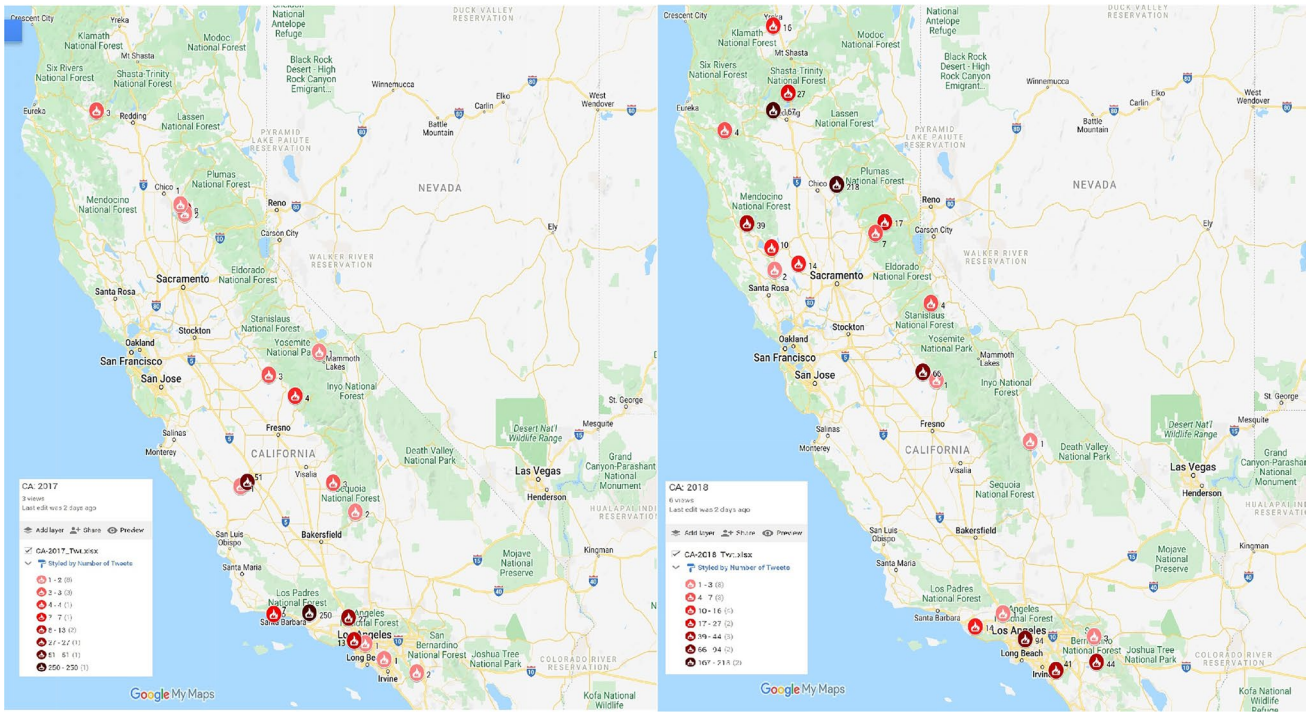

Fig. 1 Shows a Conceptual Mock-up of the Geographic Module for California in 2017 and 2018

Land Management, Fish and Wildlife Service, and the National Park Service [29]. In addition to these leading federal agencies, there are other important support and resource centers closely connected to the FWFMS. For example, the National Interagency Fire Center (NIFC) serves as the logistical and support center for the nation's wildland fires and works closely with the National Fire and Aviation Executive Board (NFAEB) to provide unified guidance and common procedures to fire agencies [30]. The National Interagency Coordination Center (NICC), which is part of NIFC, prepares the Incident Management Situation Report (IMSR) at different frequencies throughout the year to disseminate incident activity to the media and the public [30]. The current three-tiered system of support has notable strengths, including coordinated efforts between federal, state, and local agencies to manage wildfires across the country and the provision of comprehensive wildfire information through reports like the IMSR and WildfireSAFE applications, which present wildfire data in an intuitive manner. WildfireSAFE showcases the potential advantages of using a dashboard-like system for decision-makers and disseminating information efficiently to the general public. However, the system only integrates weather analysis data into existing official wildfire data without using any social media data. Additionally, there may be an overreliance on fire suppression rather than fire prevention and mitigation, which can be more effective in reducing the response time of wildfires.

In response, we propose integrating a social media analytics dashboard into such systems to enhance existing response procedures. From the standpoint of many wildfire management reports (such as IMSR, WildfireSAFE, etc.), the importance of wildfire factors in shaping managerial decisions has not been clearly claimed or defined from publicly available information. The main limitation has been the lack of transparent indicators that are consistent over time, and that measure the real-time urgency level and firefighting progress as perceived by the public, and policymakers. WildfireSAFE uses advanced remote sensing and spatial data in climate science and fire management to measure fire potential, including fuel moistures and fire danger classes from the U.S. National Fire Danger Rating System (NFDRS), Keetch-Byram and Palmer drought indices, lower atmospheric stability and satellite-derived vegetation conditions, as shown in Fig. 2 [29]. The forecasting function and integrated information in WildfireSAFE platform underpin the greater interagency fire community in the planning, response, and recovery phases of wildfire management. Despite these improvements, WildfireSAFE does not consider real-time human activity impact on the on-going wildfires, a gap where real-time social media insights could be valuable. For instance, it does not consider factors like blocked roads, downed powerlines, or evacuation orders. This is also evident in the study by Lever and Arcucci [31], which highlighted the concept of social media as a "human-sensor" for enhancing wildfire nowcasting, focusing on the innovative use of machine learning to process public engagement on platforms like Twitter. In addition to real-time human-sensor features, social media metrics can also capture the social sentiment on a wildfire. This sentiment can serve as

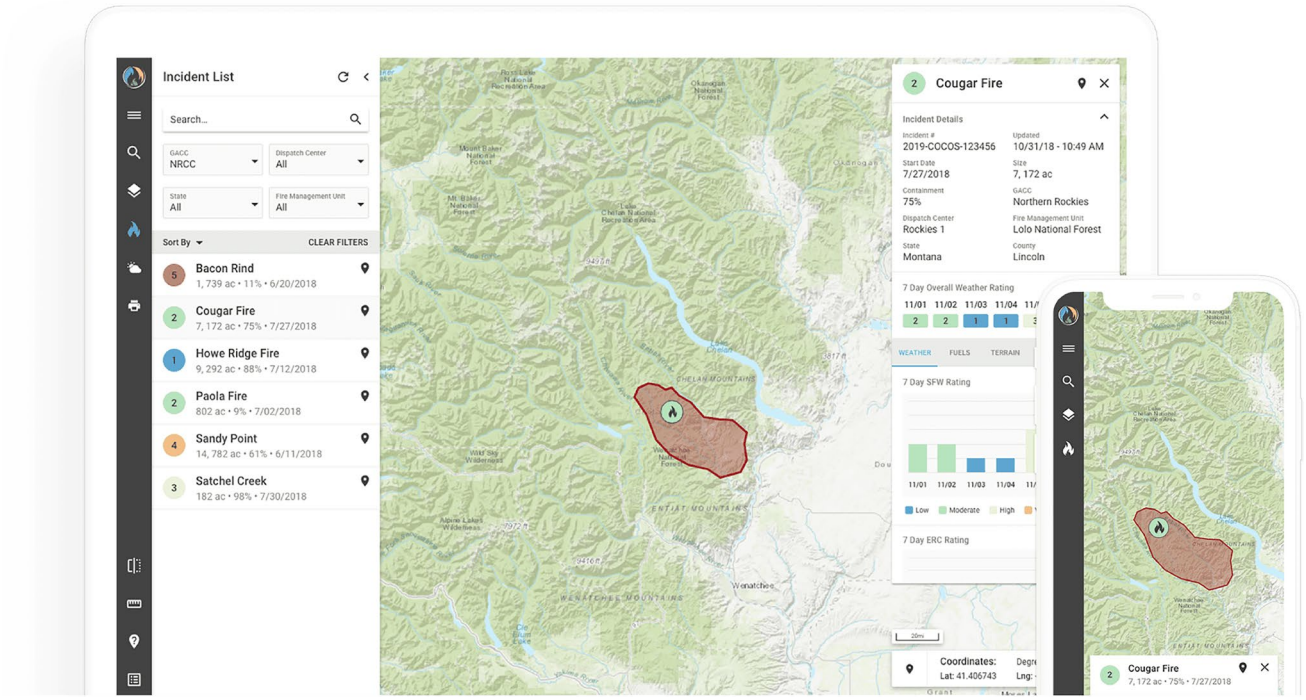

Fig. 2 The User Interface of WildfireSAFE Platform

an early indicator of a wildfire's severity. In Lever and Arcucci's study [31], they further conducted a sentimental analysis of the contents of tweets, and the results indicate that regions with lower social sentiment (or a higher amount of emotional or subjective content) often correlated with a higher perceived severity of disasters in those areas. That being said, combining social media metrics with government wildfire management data (includes IMSR and satellite data from WildfireSAFE) can improve overall wildfire management from suppression, mitigation and prevention perspectives.

6 Results: evidence based analysis

While specific applications focusing exclusively on wildfires are still limited, several studies examined the results from real-world applications of SMA across various emergency management settings. Results in these real-world applications showed promised operational improvements across various stages of the crisis. The study from Adam et al. [32] provided detailed insights into the Social Media Alert and Response to Threats to Citizens (SMART-C) program initiated by the U.S. Department of Homeland Security's Science & Technology Directorate (DHS-S&T). The program emphasizes leveraging citizen sensors, enabled by the widespread use of smartphones and other GPS-enabled devices, to provide dynamic, real-time incident information. One of the significant outcomes of the SMART-C program is the deployment of 200 Alpha phase wildland fire sensors in the U.S., Canada, and Germany, which has already shown promising early results, with several wildfires identified within 30 to 60 min of ignition [33]. Another comprehensive report from DHS-S&T [34] highlights several innovative applications of social media in emergency management. For example, the "Interactive Multimedia Website" application by the Country Fire Authority (CFA) of Victoria, Australia, was developed in response to the 2009 bushfires to enhance the management of information flow between emergency services and the community. Through platforms like Twitter (now known as X) for real-time alerts and a dedicated website for detailed dialogue and multimedia sharing, the CFA has significantly enhanced public engagement and information dissemination. Similar results were observed in the exercise conducted by Fairfax County, which aimed to assess social media's effectiveness in disaster scenarios. The test results highlighted social media as a tool for real-time communication and coordination, significantly enhancing operational outcomes. The concept of "Crisis Mapping" (akin to our heatmap used in WHS) was widely deployed in the 2010 earthquake in Port-au-Prince, Haiti. This application used the Ushahidi Platform to map geotagged social media and online content, allowing for the visualization of social media posts and photos. Furthermore, users could contribute detailed content to the platform. This innovative digital map has proved invaluable for response and recovery operations, particularly in the early stage of the crisis. International aid organizations, including the U.S. Coast Guard, the American Red Cross, and the U.S. Marine Corps, leveraged the crisis map for swift rescue operations, initially utilizing the gathered digital information for immediate response and subsequently contributing their data to enhance the platform's accuracy and utility.

Our proposed methods, integrating tailored SMA metrics, draw upon the best practices from real-world examples highlighted above. The initiative is to fully harness the advantages of social media and SMA for enhanced wildfire management. Specifically, our example of the Wildfire Social Sentiment Index (WSS) demonstrates the potential for end-users to uncover hidden information by analyzing real-time sentiments in specific regions. Furthermore, our real-time SMA integrated Dashboard exemplifies how user-generated data, combined with government-reported information, creates new possibilities for end-users to stay well-informed and take necessary precautions in a timely manner. Cost considerations also support the integration of SMA into wildfire management systems. By leveraging social media data, traditional tasks that are difficult to automate or expensive to implement can be performed more time effectively and affordably. For example, advancements in natural language processing techniques have automated sentiment analysis of social data. Moreover, the development of AI tools facilitates data collection and emergency communication, enabling end-users to access cost-effective real-time human sensing data and receive prompt assistance or responses from AI chatbots trained by official experts. Overall, integrating SMA metrics into wildfire management systems enhances the response effectiveness, reach, and affordability of emergency communication, providing valuable insights and timely support to both responders and the public.

7 Discussion: web 3.0 in wildfire management

The potential of Web 3.0 technologies in wildfire management is indeed profound and could be transformative. The synergy between Web 3.0, the Internet of Things (IoT), and emergency management is recognized through various innovative applications and research efforts. These initiatives focus on integrating IoT and Web 3.0 technologies to

enhance decision-making processes, improve situational awareness, and foster more efficient emergency response mechanisms. Yang, Yang, & Plotnick [35] proposed a modified task-technology fit approach to investigate how IoT can be incorporated into emergency response operations. It concludes that IoT technology fits the information requirements of emergency response rhythms and adds value by enabling efficient cooperation, accurate situational awareness, and complete visibility of resources. Following this, Yao, Sheng, & Dustdar [36] presented an IoT system that integrates virtual and physical worlds for efficient management of Things of Interest (TOIs). This integration is fundamental for emergency management, where rapid and efficient resource and service management can significantly impact response efforts. Meanwhile, Shamszaman et al. [37] created an emergency fire management system within the Web of Objects (WoO) infrastructure, integrating the formation and management of Virtual Objects (ViOs) derived from physical objects. This innovative system is a semantic ontology model, which is a framework for defining and interrelating Virtual Objects (ViOs) derived from real-world objects within the Web-of-Objects (WoO) infrastructure. Web 3.0 provides the foundational infrastructure that enables such a framework to be practically applied to fire emergency management. More recently, the study by Tehseen et al. [38] presented a formal model for an IoT and drone-based forest fire detection and counteraction system to enhance early detection and efficient management of forest fires. This approach marks a step forward to realizing potential synergy between Web 3.0 and IoT in the fields of early detection and efficient management of wildfires.

Concurrently, smart contracts, a blockchain feature integral to Web 3.0, can automate the allocation of resources based on data insights generated from SMA. When tied to real-time data from various sources, these contracts can optimize the release of resources under designed conditions [39]. For instance, if SMA detects an increase in social media activity suggesting a growing wildfire threat in a specific area, a smart contract could trigger the allocation of emergency resources or funding to that area without human intervention. This "smart" feature addresses significant flaws in resource planning systems, such as lack of traceability and rising costs. It also facilitates the re-scheduling and adaptation of decisions in response to system disruptions, ensuring a swift response to emerging threats. In the meantime, interoperability, another advantage of Web 3.0, can facilitate seamless communication and data sharing across different levels of wildfire management systems [10]. For example, interoperable systems could enable a national park service, local fire departments, and state emergency management agencies to access and act upon real-time social media alerts and analytics. Despite these promising features, we acknowledge that Web 3.0 technology is still in its infancy, lacking broad infrastructure, development, consolidation, and accessibility, which makes the learning curve elevated. Ultimately, the complicated functionality of Web 3.0, coupled with the lack of legitimate learning platforms, may hinder its adoption in governments [40]. Strategic planning, capacity building, and the development of user-friendly platforms and tools can address these challenges, paving the way for wider government use.

8 Conclusion

In this research, we proposed a conceptual dashboard to showcase the potential advantages of applying customized SMA metrics in wildfire management and policymaking. Our study addressed two principal aspects of SMA in wildfire management and policymaking. Firstly, we demonstrated the potential of our designed SMA metrics to improve the speed and accuracy of wildfire response efforts in the U.S. by capturing public engagement, crisis mapping, and sentiment analysis from social media data. Secondly, we examined how Web 3.0 technologies can facilitate and streamline the integration of SMA into wildfire management decision-making, enhancing time efficiency. The potential for real-time, diverse data from social media platforms like Twitter offers an unparalleled immediacy and breadth of public sentiment and perception, which are crucial in formulating effective and responsive wildfire management policies. Meanwhile, we analyzed the potential impact of emerging Web 3.0 technologies on SMA and the synergies it may connect other advanced technologies, such as IoT and AI, to wildfire management in the future. We highlighted that the decentralized, secure, and user-driven nature of Web 3.0 could revolutionize information collection and dissemination, making SMA incorporation easier and more efficient. We also analyzed the WildfireSAFE Platform, an innovative dashboard-like system that leverages climate data and forecasts to enhance the accuracy of wildfire prediction and monitoring. However, this system only integrates weather analysis data into existing official wildfire data without using any social media data. Thus, we propose further integrating our customized SMA metrics into a dashboard to enhance existing wildfire management systems. Moreover, we evaluated the integration of our SMA metrics and their advantages by reviewing real-world applications of SMA in emergency management and related research. This examination highlights SMA's potential for enhancing accurate and rapid response capabilities in disaster situations.

Moving forward, future research should focus on refining these conceptual SMA metrics integration and addressing the challenges associated with social media data use in governmental policymaking. Efforts should be directed towards developing strategies that address misinformation, expanding the integration scope to encompass various types of social media data beyond just textual content. This approach promises to unveil fresh perspectives and enhance wildfire management strategies. Moreover, understanding the dynamics of content creation and monitoring within governmental frameworks will be critical for effective policymaking. The proposed SMA metrics in this study pave the way for the advancement of scalable, real-time wildfire management systems integrated with SMA. These SMA metrics are designed to enhance emergency management and disaster response capabilities, aiming to mitigate the risks associated with delayed rescue during wildfires from a policymaking perspective.

Author contributions CRediT Author StatementGarros Gong: Writing - Original Draft, Conceptualization, Methodology, Software, Writing - Review & Editing.Stanko Dimitrov: Supervision.Michael R. Bartolacci: Supervision.

Funding No funds, grants, or other support was received. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Data availability The datasets are not publicly available as the main discourse of the article is centered around a Conceptual Model without actual data analysis. A minor portion of the data, used for visualization purposes, is derived from a larger dataset crucial to two other unpublished papers, where the novelty lies in the dataset's uniqueness. To preserve the integrity of the ongoing research, this data is withheld but can be provided to reviewers upon request during the review process.

Declarations

Research involving human participants and/or animals This research did not involve human participants or animals. Therefore, it did not require any ethical approval in accordance with the institutional and/or national research committee's requirements.

Consent for publication Not applicable, as our research did not involve human participants.

Competing interests The authors declare that there are no conflicts of interest regarding the publication of this paper. No financial or personal relationships have influenced the outcomes of this research.

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