Geo: Geography and Environment

WILEY | Open Access Geo Royal Geographical Society with IBG

SPECIAL SECTION OPEN ACCESS

Mapping Fire Management: A Spatial Social Network Approach

Christoph Neger[1] | Cody Evers[2] | Kapil Yadav[3] | Octavio Romero Cuapio[4]

[1]Academic Unit of Territorial Studies Yucatán, Institute of Geography, National Autonomous University of Mexico, Mérida, Mexico | [2]Department of Environmental Science and Management, Portland State University, Portland, Oregon, USA | [3]Royal Holloway, University of London, London, UK | [4]National Preparatory School, National Autonomous University of Mexico, Mexico City, Mexico

Correspondence: Kapil Yadav (kapil.yadav@rhul.ac.uk)

Received: 6 May 2025 | **Revised:** 5 February 2026 | **Accepted:** 10 February 2026

Keywords: fire governance | multi-scale networks | social network analysis | thematic cartography | wildfire management

ABSTRACT

Maps are an essential tool to inform fire governance and management. For instance, they can highlight which areas are most vulnerable to adverse fire impacts or be used to plan interventions for risk reduction and prevention. In recent years, several studies have mapped the fire management activities and the networks between the multitude of involved actors. They build upon previous advances to combine quantitative and qualitative social network analysis with geographical analysis and cartography, aiming to highlight areas of opportunity to enhance fire governance. This paper continues this line of research, examining cooperation in fire management within the south-eastern part of the state of Chiapas. This area is the main fire risk area in Southern Mexico, characterised by the involvement of many different fire management actors. The paper proposes two advances to better visualise the networks between these actors—integration with modularity clustering and a thematic map integrating different spatial scales—and discusses the implications of these fire network maps for governance. The paper's main results are, first, the confirmation of the considerable influence of spatial distance and aspects of human and physical geography on network formation. Second, it shows the capacity of mapping to inform regional fire management arrangements.

1 | Introduction

Wildfires represent one of the main management challenges for the conservation of forest landscapes in the tropics, with soaring numbers of burned areas and fire intensity in many regions of the world, accompanied by a steady increase in climatic fire risk (Bowman et al. 2020; Ellis et al. 2021; Jolly et al. 2015; Le Page et al. 2017; Wasserman and Mueller 2023). Almost all fires within the tropics are human-caused (Archibald et al. 2013) and are often tied to land management, some of which have been practised for thousands of years (Bowman et al. 2011). Despite the long-standing connection between humans and fire, it has only been over the last two decades that there has been an increasing interest in academia in the social aspects of fire use and management (McCaffrey et al. 2012; Moore 2019). In this context, an important branch of research studies the fire use practices of local and indigenous communities (cultural fire management) and their interaction with Western fire management approaches (intercultural fire management) (Bilbao et al. 2019; Ponce-Calderón et al. 2022); another important branch is the studying of the networks formed by the social actors involved in wildfire prevention and suppression, which are organised in networks of social actors, based on the realisation that no single organisation can usually tackle this problem in a given area on its own (Faas et al. 2019).

Social networks provide critical insights into these management challenges by describing how social actors (defined depending on the study context, referring mostly to individuals, communities or organisations) coordinate their actions through contact, information sharing, flow of resources and the like (Andris 2016; Wilkin et al. 2019).

Early examples of publications focusing on social networks in fire management are Goldstein and Butler (2010) regarding a learning network and Owen et al. (2012), tackling the information-sharing processes between meteorologists and fire management professionals. The issue became the primary interest of extended research projects in the US, such as the Fire Chasers project (Fleming et al. 2015; Nowell and Steelman 2019) and the Forest, People, Fire project (Fischer et al. 2012). Beyond the North American context, while not applying specific social network analysis terminology and methods, social relations are an important aspect in the literature on integrated fire management (Silva et al. 2010) and, more recently, fire governance (Tedim et al. 2020) and intercultural fire management (Bilbao et al. 2019; Mistry et al. 2019).

At the same time, researchers focusing on general aspects of social network analysis have started to look into the relationship of social networks and space, recognising that spatial proximity is a crucial factor for network formation. In these studies, nodes are placed at specific geographical coordinates to look at the difference between social (network) distance (measured only in terms of connections in the network, also termed functional or effective distance) and physical distance depending on geographical coordinates (Andris 2016; Andris et al. 2018).

A growing collection of studies is exploring techniques for visualising and analysing the spatial dimensions of these social networks. By putting the fire management networks on a map, researchers expect to enhance the interpretation of network patterns and shed light on aspects that would go unnoticed in classical quantitative social network analysis. Previous advances in this context include the following: the superposition of a geographical social network layout (between jurisdictional fire management authorities) over a blank map of the study area and its comparison with a map of fire transmission between jurisdictions, highlighting existing collaboration gaps (Hamilton et al. 2019); the comparison of a classical network layout of actors involved in fire management and the geographical position of nodes on a topographic map according to their working area, showing the influence of proximity of these work locations on actor collaboration (Evers 2020); a visualisation of actor cooperation over a map of administrative boundaries, locating actors according to their headquarters and showing the areas with most active cooperation (Neger 2021); and the integration of a similar map of network nodes on a map that included other aspects of the study area's geographical context, underlining the importance of, for instance, topography, road distances and the location of fires (Neger et al. 2024).

This paper examines how spatial proximity and institutional scale shape cooperation among fire management actors in Southeastern Chiapas, the area with most wildfires in the South of Mexico (Pompa-García et al. 2018) and with a diversity of actors involved in fire management (Huffman 2010). By integrating social network and geographical analysis, the study asks: (1) How do federal, state, municipal and community actors interact in social networks across scales during fire events, and how do these interactions produce regions of cooperation and fragmentation? (2) How are these functional cooperation networks related to formal administrative boundaries and the location of administrative centres? (3) How do physical geography (e.g., mountainous terrain, coastal location) and fire characteristics (size and duration) constrain or facilitate coordination among actors? To answer these questions, the paper aims at depicting the wildfire response network in space and using network cluster analyses to compare management communities to underlying jurisdictional boundaries. The research uses an inductive approach to identify the specific network patterns of this case study, without a preconceived notion of potential outcomes. In answering these research questions, it seeks to arrive at a deeper understanding of the reasons behind network formation and obtain relevant insights to enhance regional fire governance.

2 | Methodology

2.1 | Study Area

The paper focuses on three administrative regions in the Southeast of the state of Chiapas, Mexico: Valles Zoque, Frailesca and Istmo-Costa, an area covering 21,114 km^2, consisting of 14 municipalities, and bordering the state of Oaxaca and the Pacific Ocean (Figure 1). The regional boundaries broadly relate to the area's geomorphology. Istmo-Costa covers the coastal plains and is limited inland by the Sierra Madre de Chiapas, a major watershed with elevations of up to more than 4000 m; the other two regions contain the higher elevations of the Sierra Madre and their northern foothills, followed by the highlands of Chiapas in the case of Valles Zoque—an area characterised by karstic valleys and mountains—and by the state's central depression in the case of the Frailesca region. The study area is highly biodiverse, comprising several protected areas (four biosphere reserves, Selva El Ocote, La Sepultura, El Triunfo and La Encrucijada; and the Area for the Protection of Natural Resources La Frailescana) and different ecosystems, including fire sensitive tropical rainforest, tropical dry forest and cloud forest, relatively fire-adapted oak forest, as well as fire-dependent pine forest and savannah (Comisión Nacional para el Uso y Conocimiento de la Biodiversidad 2013).

The area's population in 2020 was 747,297 (285,360 in Frailesca, 230,371 in Istmo-Costa and 226,566 in Valles Zoque), with a relatively low overall population density of 35.4 hab./km^2 (highest in Istmo-Costa with 42.9 hab./km^2 and considerably lower in Frailesca with 34.3 hab./km^2 and Valles Zoque with 30.6 hab./km^2). A large part of the population (289,495 inhabitants, 39.2% of the total) is concentrated in the municipal seats of the 13 municipalities that make up a region (Figure 1), which are usually larger towns with a population between 49,201 (Cintalapa) and 3191 (Montecristo); the only exception with less population is the municipal seat of Luis Ángel Vidal with only 638 inhabitants. This leaves the remaining areas of the regions even more sparsely populated; only four other towns have more than 5000 inhabitants and 228,370 (31.9%) live in villages with a population of <1000, especially in the mountainous areas at the regions' borders. Most of the area's rural population lives in ejidos, communities governed by assemblies of smallholders; a

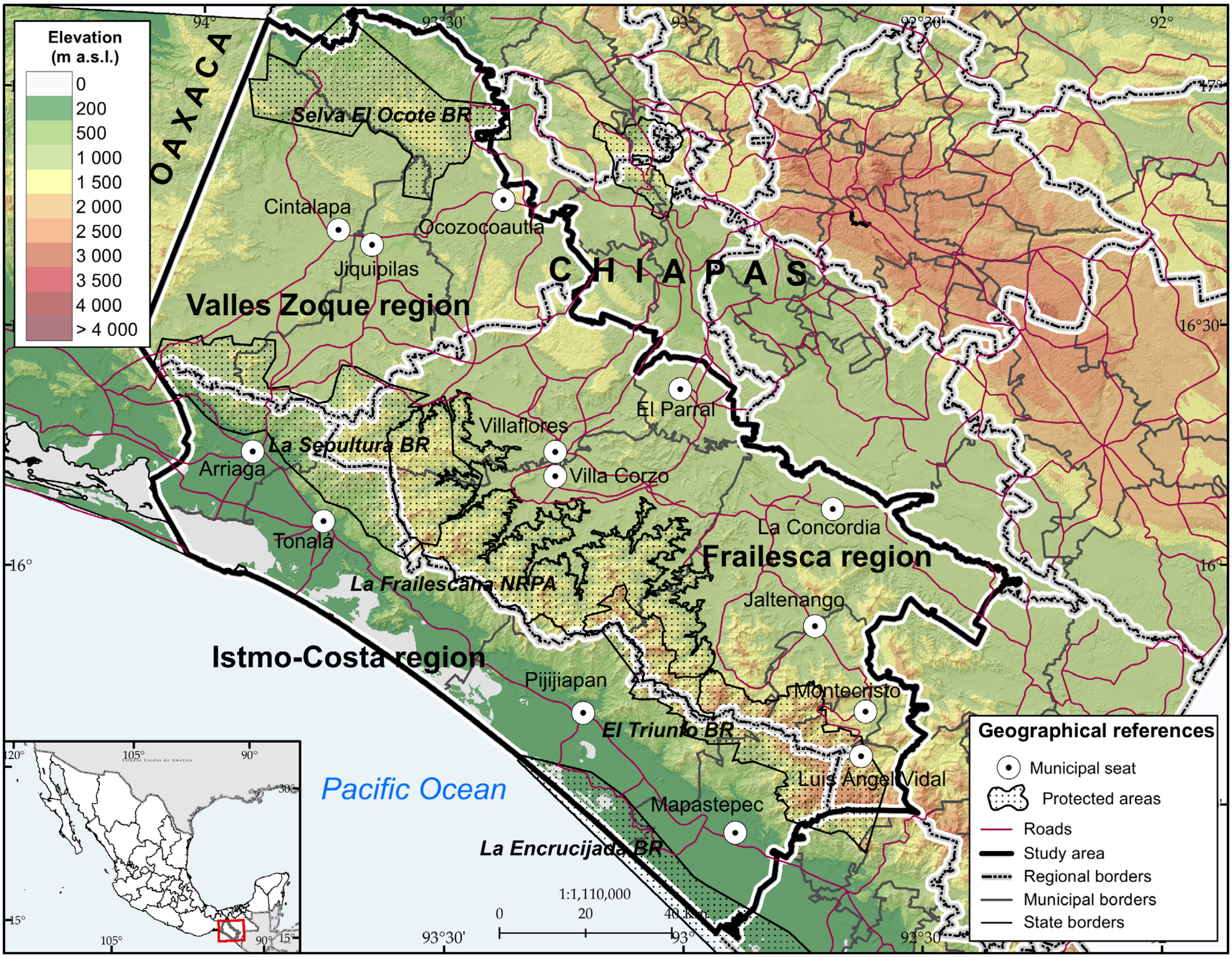

FIGURE 1 | Study area of the Southeast of Chiapas, Mexico. For enhanced readability of the map, some names are shortened, such as 'Cintalapa' instead of 'Cintalapa de Figueroa' and 'Jaltenango' instead of 'Jaltenango de la Paz'. In Mexico, municipalities usually hold the name of their municipal seats; Jaltenango is an exception to this rule: the surrounding municipality is named Ángel Albino Corzo. Abbreviations for protected areas: BR, biosphere reserve; NRPA, natural resources protection area.

considerable number of them identify themselves as indigenous (6.9% of the total regional population and 19.9% of those living in villages of between 10 and 1000 inhabitants) (Instituto Nacional de Estadística y Geografía 2021).

Pompa-García et al. (2018) identified the area as the southernmost of Mexico's wildfire hotspots. Between 2019 and 2023, the area constantly reported the highest wildfire numbers in Chiapas, with a total number of 1157 fires during the 5 years (62.9% of all fires in the state) and 182,241 burned hectares (82.8%) (Comisión Nacional Forestal 2025). Firefighting in the area, according to the Mexican forest law, is a joint responsibility of local landowners, municipalities, protected area authorities and, in the case of larger fires, state and federal institutions. As reported by the CONAFOR (National Forestry Commission) and observed by the authors during previous studies, it is usually an activity with comparably low technification, without the use of heavy machinery, fire trucks or airplanes; helicopters are used very rarely to access areas that are difficult to reach. Due to the steep terrain and the frequent strong winds, firefighters usually avoid combatting the flames directly. Usually firefighting effort consist of one or several brigades of about 10 persons each, conducting a first assessment of the situation, based on thermal hotspots and the observation of plumes of smoke in field; then they go about containing the fire with the elaboration of fire breaks—lines that are several metres wide where all combustible vegetation is removed by using minor equipment such as machetes and McLeod tools. Finally, the firefighters revise burned areas and put out any embers. Afterwards, the person responsible for managing the event, usually a representative of the organisation arriving first at the fire, sends a report to the state fire centre; this might not be the case if a fire was attended by non-governmental actors on their own, such as local communities.

2.2 | Data Acquisition and Analysis

We used daily fire registers produced by the operative technical group for fire management of the state of Chiapas for 2023, with a total of 164 registered wildfires in the study area (62 fires in Valles Zoque, 82 fires in Frailesca and 19 fires in Istmo-Costa), affecting 15,885 ha, with a medium duration of 2.2 days. These are detailed internal data of the involved governmental agencies, which are generally not open to the public; only a very generalised summary gets published at the national level. This database includes all fires affecting forest vegetation that were attended and reported by federal, state and municipal actors involved in fire management. In terms of comparison, remote sensing data accounted for 302 fires in the area in the same period; however, this might include prescribed and agricultural burns (99 fires consist of only one pixel, thus, they might refer to small burning events) as well as uncontrolled fires on fields and artificial grasslands (Verleye 2024). These data include information regarding the geographic location of the reported wildfires (estate, municipality, region, geographical coordinates), an estimation of burned hectares and information regarding the actors involved in firefighting (name of the person in charge of the event, number of personnel of each involved organisation or community); as they are daily data, it is also possible to know the duration of each fire event. For the analysis of the data, they were transferred into an Excel sheet, summarising the data from fires that appear in several reports and standardising the actor identifications. Several phone calls with staff from CONANP (National Commission of Protected Natural Areas) and the CONAFOR served to clarify confusing actor names. Fifteen cases were dropped from the analysis because it was impossible to identify specific actors, resulting in a total of 95 different actors (representatives of governmental institutions, wildfire brigades, local communities and, in a few cases, actors from the private sector), whose interactions were analysed in this study.

These data were developed into social networks with Python software (https://www.python.org/) using Pandas and Networkx. The resulting networks consisted of a list of nodes (the actors involved in firefighting) and a list of edges (links between the actors who participated fighting the same fires), with weights assigned to the edges according to the number of times each actor cooperated with another. A node list comprised actor attributes, including the coordinates of their permanent geographical location and, afterwards, the calculation of network statistics (network centrality measures and modularity clustering) and the application of network layouts in the open-source network analysis program Gephi (https://gephi.github.io/), including the plugin GeoLayout for the visualisation of the network according to the node's geographical locations. These locations show the actors' headquarters or usual meeting places. This includes the local or regional representations of federal and state actors, who usually have a permanent station or headquarter in the area where they are working.

We collected the relevant geodata (topography, roads, localities, borders) obtained from the Mexican Institute for Statistics and Geography (https://www.inegi.org.mx/) and the data on individual fires obtained from the daily fire registers and assembled this data using the QGIS software (https://qgis.org/). The objective of combining this geographical information and the network data from Gephi directly in the GIS proved to be unfeasible in the present case, contrary to previous applications in this field (Neger et al. 2024). This was due to the fact that the headquarters of many actors were located within the same towns or in nearby communities; therefore, on the regional map the nodes would appear as superposed. This is particularly problematic for the visual interpretation of the results, as some nodes and the connections between actors located in the same or nearby towns would not be visible. In Gephi, this issue can be resolved using the Noverlap algorithm, which spreads nodes in a determined radius (we used a threshold of 1.3, which means that other nodes are placed at a distance that corresponds to 30% of the node symbol's radius, leaving enough space to show the lines between the nodes); however, this information is lost when transferring the data to Shapefile or Keyhole Markup Language (KLM) format. it is possible to replicate this visual spreading of points with point displacement tools available in GIS programs, but with the disadvantage of disconnecting the network nodes from their corresponding edges. To tackle this issue, the paper followed the approach of Grandjean (2015), extracting the cartographic map and the Geolayout network map as scalable vector graphics (SVG) and connecting them in the graphic program Inkscape (https://inkscape.org/), aiming at the highest level of spatial accuracy possible.

3 | Results

The study identified a relatively dense and complex network of a multitude of actors involved in fire management in Southeastern Chiapas in the year 2023, summarised in Table 1 and represented on the maps in Figures 2–4. The overall network consisted of 95 nodes (actors placed at a specific location). It includes four located outside the region in neighbouring municipalities, who cooperate with actors within the study area. As stated in the Methodology, the area is divided into three administrative regions. Most actors are found within the Valles Zoque (46) and Frailesca (40) regions, whereas the Istmo-Costa region only holds six actors.

Only in 3.8% of the events, actors attended a fire on their own. Overall, on average, 4.6 actors worked together in the suppression of each fire, with a maximum of 17; the correlation between the duration of the fires (Pearson correlation of 0.044 and Spearman correlation of 0.015) and fire size in terms of hectares (Pearson correlation of −0.010 and Spearman correlation of 0.111) with the number of actors involved was very weak. In total, these cooperations in fire suppression resulted in 412 connections where one actor cooperated with another in firefighting at least once during the year 2023. This implies an overall relatively low network density of 0.092, which means that existing connections account for 9.2% in comparison to the full potential number of connections in the network, given the number of nodes (if each node would be connected with every other node). The density is higher within the regions, with a particularly high number of 0.6 in the Istmo-Costa region, which means that although there are only a few actors, the majority of them are connected between each other. In terms of absolute numbers of connections, the Valles Zoque region stands out, with a total of 223 connections, which means that every actor in the regional network cooperated on average with 9.9 other actors.

These first observations—the regional disparities and the fact that connections are denser at the regional level and that the network is more dispersed when looking at the whole study area—already give a hint of the importance of space in the formation of the network. Figure 2 makes this clearer. Its key messages are the comparison of the situation of the network compared to,

TABLE 1 | Basic data of the fire management network in Southeastern Chiapas (2023).

Network metrics	Valles Zoque region	Istmo-Costa region	Frailesca region	Whole study area	Whole study area including connections to neighbouring regions
Nodes	45	6	40	91	95
Connections	223	9	97	388	412
Connections to neighbouring regions	55	23	56	24	—
Network density	0.225	0.6	0.123	0.095	0.092
Average degree	9.9	3	4.8	8.5	8.7
Main actors by degree	1. State civil protection regional brigade Valles Zoque (30) 2. La Sepultura biosphere reserve administration-CONANP (27) 3. Mexican Military station Cintalapa (23) 4. Forest protection and fire management brigade Cintalapa (23) 5. CONAFOR regional brigade Valles Zoque (23)	1. State civil protection regional brigade Istmo-Costa (4) 2. Municipal Civil Protection Arriaga (4) 3. State civil protection regional delegate Istmo-Costa (4) 4. Rural brigade Arriaga (3) 5. Forest protection and fire management brigade Arriaga (3)	1. State civil protection regional brigade Frailesca (18) 2. CONAFOR regional brigade Frailesca (15) 3. Municipal Civil Protection La Concordia (13) 4. Municipal Civil Protection Ángel Albino Corzo (12) 5. La Frailescana reserve contingency brigade (10)	1. La Sepultura Biosphere reserved administration-CONANP (50) 2. State civil protection regional brigade Valles Zoque (35) 3. Mexican military station Cintalapa (33) 4. Forest protection and fire management brigade Cintalapa (24) 5. CONAFOR regional brigade Valles Zoque (24)	1. La Sepultura Biosphere reserve administration-CONANP (50) 2. State civil protection regional brigade Valles Zoque (35) 3. Mexican Military station Cintalapa (35) 4. Forest protection and fire management brigade Cintalapa (25) 5. CONAFOR regional brigade Valles Zoque (25)

Note: With the exception of the last column, the information on nodes, connections, density and degree refers to connections within the regions.

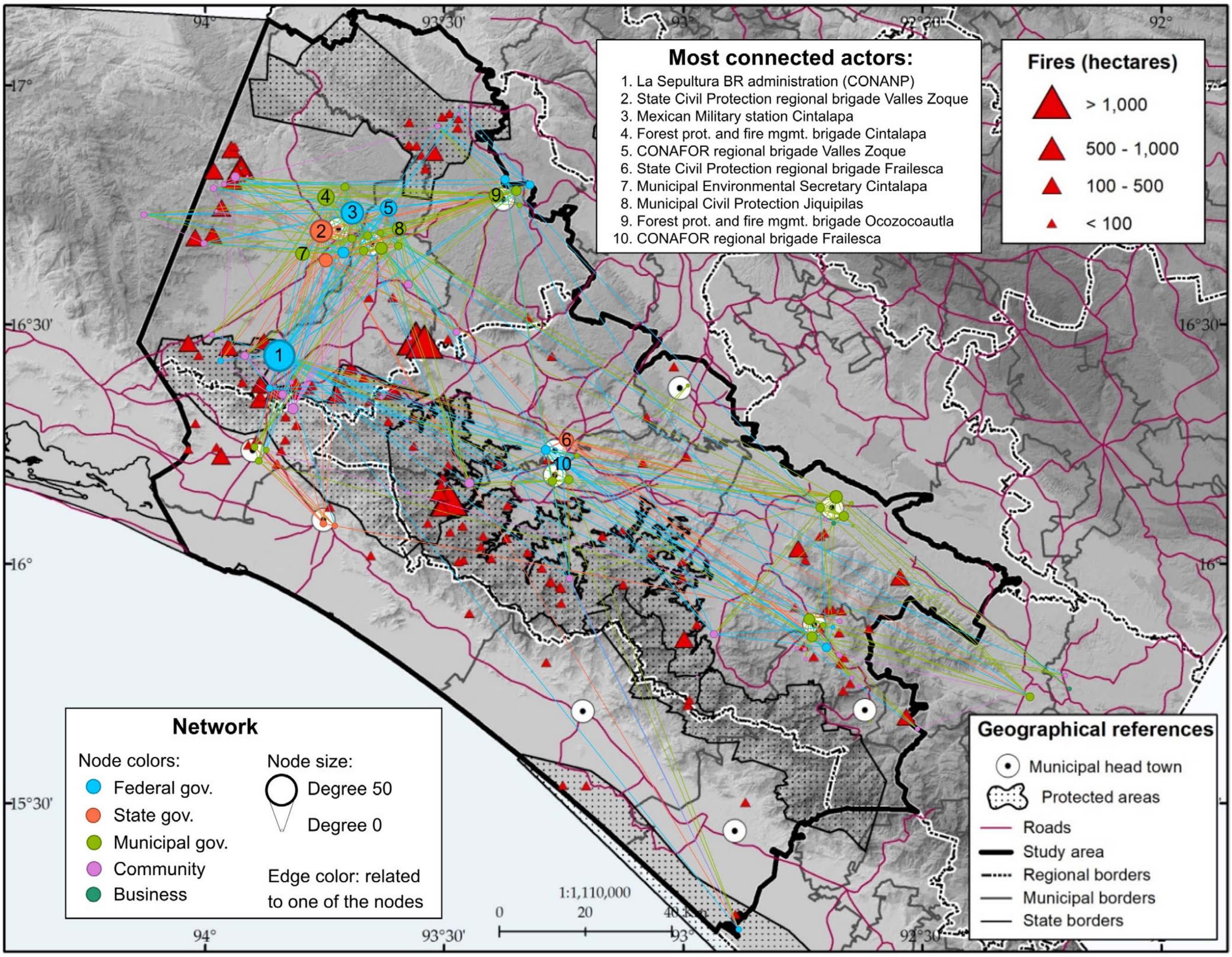

FIGURE 2 | Spatial social network for fire suppression embedded in their geographical context and fire characteristics in Southeastern Chiapas (2023).

first, the study area's overall geography and, second, of 160 fire events that took place in 2023 (for four fire registries, there were no clear geographical coordinates). Regarding the first point, the visualisation includes the area's topography in the form of an altimetric map, administrative borders, protected areas, places of regional administrative centres (municipal seats) and roads. The cartographic interpretation of this representation offers several insights into the formation of the network in its geographical context and the network actors.

The actor with the most connections is the administrative office of the La Sepultura biosphere reserve, located at the reserve's boundary, which is the reserve with the most significant fires within its boundaries and in its close surroundings. All other actors with a high number of connections are located very closely in municipal seats (underlining the importance of the visualisation using the Noverlap function), with the highest concentration in the nearby municipal seats of Cintalapa and Jiquipilas, in the municipalities with the highest incidence of large wildfires. The most connected actors are federal (protected area authorities and the CONAFOR) and state actors (mostly the state government's Civil Protection agency); municipal actors generally have intermediate network centrality values, with the lowest values shown by local communities, although there are exceptions of, for instance, more central community actors (referring to community fire brigades that help out in other areas beyond their community) and less connected state actors, such as those located in areas with lower fire incidence.

Regarding the second key message of Figure 2, there is much more actor involvement and cooperation in regions and municipalities with a high fire incidence. However, the most connected actors' headquarters (except La Sepultura's administrative office) are mostly located relatively far away from the precise fire locations. In general, there are many more short-range connections than those that span large spatial distances. However, there are some notable exceptions, especially in the case of actors located in areas with little fire incidence, which might show strategic, temporal movements of these actors to more fire-prone areas.

Most connections are within the study area, with interregional cooperation, although the densest sub-networks are within administrative regions. There are fewer fires along the region's boundaries, which might be a reason for the lower collaboration with other regions within Chiapas. The only

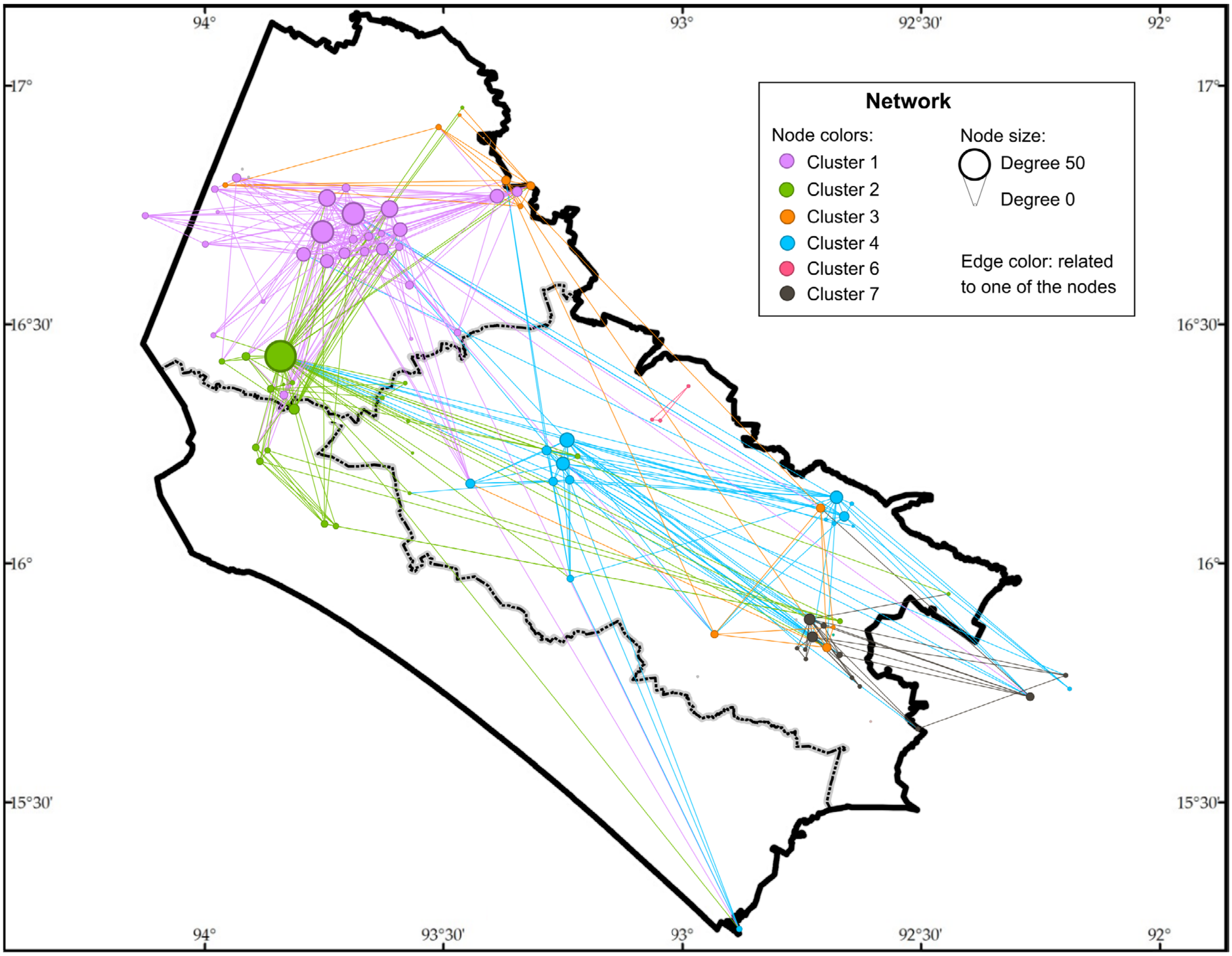

FIGURE 3 | Spatial social network of fire suppression in Southeastern Chiapas (2023) related to modularity clusters.

exceptions are several fires along the border with the state of Oaxaca, but cooperation is scarce, which might relate to the area's mountainous terrain and limited accessibility by road. Relatedly, topography and accessibility seem to influence the network structure decisively, most evident in the little involvement of actors in the coastal area beyond the main mountain range that crosses the study region from north-west to south-east, along the limits of the Istmo-Costa region with the other regions. Also, the limits of the state of Oaxaca and the study area are defined by mountains, whereas the limits between the Valles Zoque and the Istmo Costa region are marked by hills of less height. Both aspects, topography and accessibility, are strongly related, due to the difficulty to construct and maintain roads in mountain regions. Within the study area, there is only one road crossing the mountains, in the northern part, close to the town of Arriaga, which is clearly reflected in the network relations.

While aspects such as fire locations, accessibility and topography are important, the present study underlines spatial distance as the defining feature in spatial social network analysis, as shown in Figures 3 and 4. Figure 3 uses a cluster analysis method widely used in social network analysis (modularity clustering) that only considers the social relationships between actors. Despite not considering any geographical data, when putting the resulting clusters on a network map with a geographical layout, they show a clearly spatial distribution, except cluster 3, which groups actors whose connections are shared mainly with actors from other regions, so in this cluster, spatial distances are less relevant. Yet the majority of actors, and all with the highest centrality values, are located in the clusters that are clearly spatially defined. To revise the correctness of this visual interpretation, we conducted a statistical test (*t*-test) of the average distances of the nodes within each cluster. The results underlined the impression given by the map, with much lower inside mean distances of node connections than outside mean distances for clusters 1, 2, 4 and 7, which together include 82% of all the nodes (cluster 1: inside mean 26 km vs. outside mean 94 km; cluster 2: 51 km vs. 82 km; cluster 4: 54 km vs. 93 km; cluster 7: 23 km vs. 119 km); on the contrary, in cluster 3, the inside mean distance (81 km) was very close to the outside mean distance (85 km). Moreover, this visualisation represents which regional centres are more connected to each other, appearing within the same clusters, and in which areas there are overlaps of two clusters.

Figure 4 combines the advantages of classical social network layouts and spatial representation. Moreover, it underlines

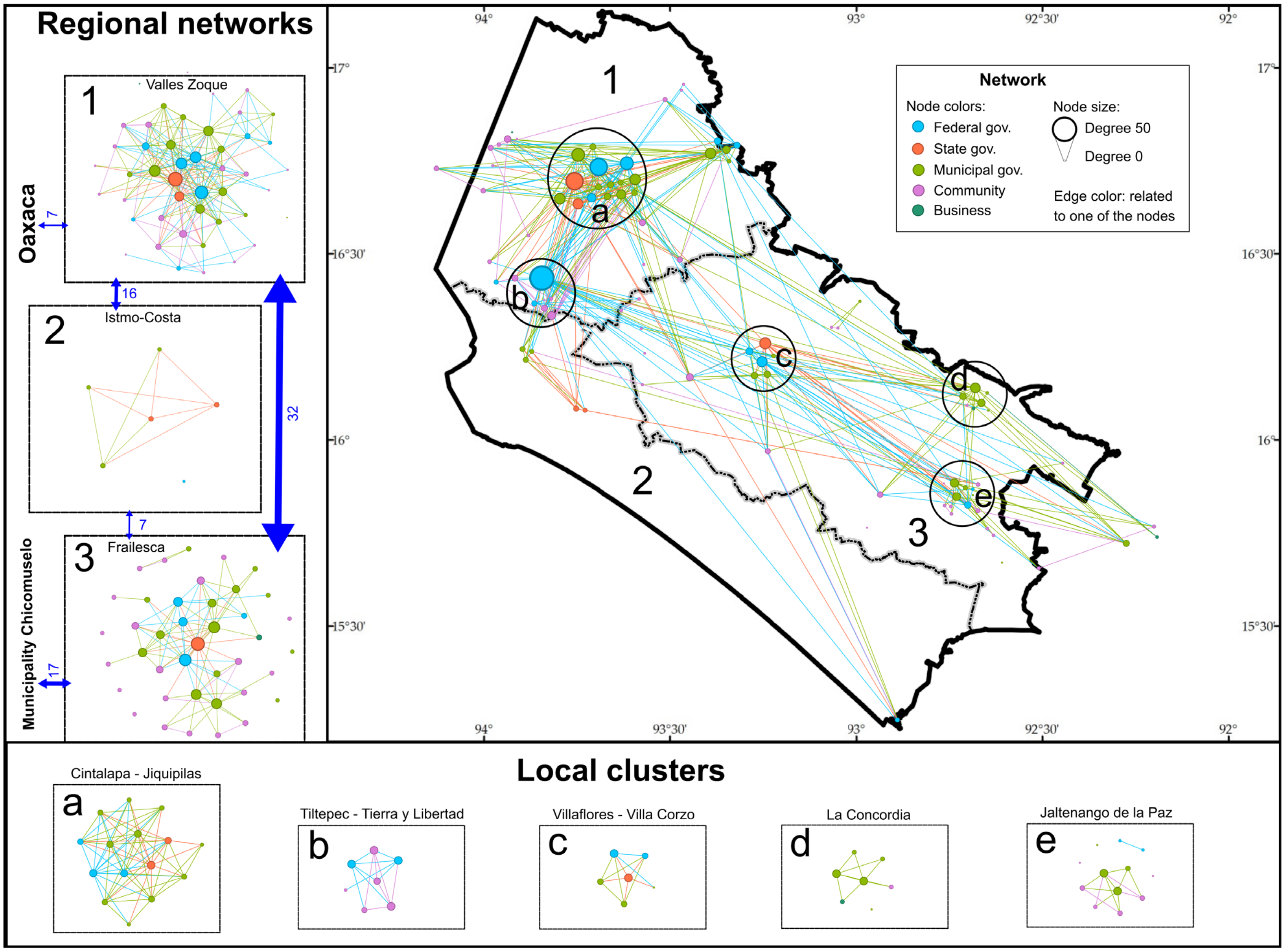

FIGURE 4 | Representation of networks at multiple scales in Southeastern Chiapas (2023). The study area map shows a Geolayout representation and the regional and local networks have a Fruchterman-Reingold network layout; the blue arrows indicate interregional connections.

the multiscale nature of fire management networks. An orientational map with a georeferenced network layout defines the geographical definition of subregions and regional centres; regions are defined by manually drawn lines instead of exact regional boundaries due to the slightly inexact location of some points resulting from the Noverlap function that spreads superposed nodes. Connections within these subnetworks appear in separate images with a force layout representation to visualise social relations at the regional and local levels. Arrows between these levels highlight inter-regional connections.

This approach shows the differences between the three regions that make up the study area, apparent also in Table 1, with two regions with a considerable number of nodes, Valles Zoque (regional network 1) and Frailesca (regional network 3), and one region with much fewer nodes, Istmo Costa (regional network 2). Valles Zoque is spatially much more compact than Frailesca and has a much denser network. Istmo-Costa is a small network, but mostly all nodes are connected. While Figure 4 does not name individual actors, the colouring of actor types indicates changes in actor roles, especially in the case of Valles Zoque. While federal actors are most connected within the study area as a whole, state and municipal actors appear more prominent in terms of connections at the level of the subregions.

Figure 4 also highlights the existence of several local clusters of nodes concentrated in one or two spatially close towns, identified by visual interpretation of the map. Most of them comprise a connected web of six to seven nodes, except for 15 connected nodes in the case of the Cintalapa-Jiquipilas network. In addition, in two cases, there are disconnected nodes, one in the case of La Concordia and two single nodes, as well as a dyad (connection of two nodes) in the case of Jaltenango de la Paz. Apart from these exceptions, the local networks are densely connected, with links between almost all of their nodes and almost all nodes at a similar position within these networks, contrary to their differences at other network levels; this is related to connections outside the local network. The local networks are situated around municipal seats made up mostly of federal, state and municipal actors, with the exception of Tiltepec-Tierra y Libertad. These two rural towns hold the administrative office of the La Sepultura biosphere and some of the most important community brigades. In the west of the Valles Zoque region, there is an additional agglomeration of closely located nodes, almost all community actors. However, they were not identified as a local cluster, as there are no connections between them; they entirely depend on assistance from other areas.

4 | Discussion

4.1 | Novel Methodological Applications in Mapping Social-Spatial Networks

The present paper presented novel methodological applications in mapping spatial social networks. It started by replicating techniques from previous studies in a different spatial context and at a different level of complexity, showing the social network within its geographical context. Compared to previous works such as Neger et al. (2024), the main difficulty in this approach was the existence of spatially overlapping nodes, that is, actors whose headquarter locations are so close that they appear superposed on the regional map, which made it necessary to apply a non-overlap function at the cost of spatial precision. This endeavour was incompatible with previous advances in combining GIS and social network software, and it was necessary to go back to integrating social network and geographical data via graphical editing, an approach that Grandjean (2015). To reduce the resulting spatial inaccuracy, fixed anchor points were added to the social network and in the maps produced with GIS.

The integration of social network clustering not only proved to be a valuable addition, showing the importance of spatial proximity, but also highlighting cases when spatial proximity is not the decisive factor for nodes to connect or not connect, due to the role of other geographical factors such as topography and accessibility or due to node attributes that are not tied to the nodes' geographical location, such as homophily of actors' institutional affiliations and responsibilities (as in the case of the brigades of biosphere reserves helping out in other biosphere reserves). The present approach used the modularity clustering method included in the standard Gephi package. Future studies might experiment with distinct clustering methods, with defining clear spatial boundaries of clusters and with combining social network (Hoffman et al. 2017) and spatial (Baykal 2025; Pimpler 2017) clustering techniques, as well as advances in the combination of spatial analysis and different ways of clustering that take into account the specific attributes of the network nodes (Han et al. 2024; Zhang et al. 2025). Also, de Spatial Tabu Optimization for Community Structure (STOCS) approach developed by Guo et al. (2018) might offer a promising tool to further advance and classify network communities, by transforming trajectory data (which might be derived from social network relations) into spatial data.

While the comparison of social network clusters and spatial proximity justifies the need to study social networks from a geographical perspective, the multiscale representation of networks is best understood as a further progression of spatial social network analysis. The spatial representation identifies local clusters, which are then analysed from a social network perspective, adding to the analysis and visualisation of the multiscale nature of social networks (Di Gregorio et al. 2019). To avoid the representation from getting too confusing, the multiscale representation here was separated from the map that shows the network in its geographical context, reverting to using a simple base map for localisation. However, it might be possible to integrate this approach with selected non-social network variables, similar to the combination of ecological and social networks of Hamilton et al. (2019). In this context, wildfire locations could appear in the map as nodes as well, showing the connections between the places where the stakeholders come from and where they go to suppress fires.

The cartographic approach presented in this article to understanding collaboration among actors in geographical space could be augmented in future work using network null models. Such models provide a statistical framework for evaluating whether observed patterns of cooperation differ significantly from what would be expected by chance, given basic structural or spatial constraints. For example, degree-preserving randomisations (Faust 2007) could test whether the network's clustering or centralisation arises simply from differences in actor activity levels, while spatially embedded configuration models (Expert et al. 2011) could assess whether the observed localisation of ties reflects more than just geographic proximity. Incorporating these null models would allow disentangling the relative contributions of spatial distance, institutional hierarchy and other contextual factors to the formation of cooperative ties.

4.2 | Implications for Managing Wildfire in Southern Mexico

Besides its methodological innovations, the results of this paper include concrete implications for fire management in the state of Chiapas, Mexico. The maps show that most actors identified in the official fire data used here are located in municipal seats, whereas most fires happen in mountain areas that are relatively far away from these towns. This underlines the importance of supporting the fire management capacity of local communities, which, given their location, could respond more quickly and avoid fires from spreading. Furthermore, their inclusion might bring about benefits related to their local knowledge and cultural fire management practices, adapted to each place's specific conditions (Bilbao et al. 2019; Ponce-Calderón et al. 2022).

Within the identified networks, a few federal and state actors are central to the connections of regional fire management networks, underlining the crucial role of governmental bodies such as CONANP and CONAFOR (both chronically underfunded and subject to dwindling budgets in recent years, as outlined by Madrid 2020) in coordinating fire management efforts. These results also confirm the observation of previous studies, such as those of Evers (2020) and Neger et al. (2024), that actors working at higher spatial levels tend to be more connected, both regarding connections within this actor group and of their relations with other actors. On the contrary, there tends to be little cooperation among neighbouring local actors. However, there are some exceptions, such as the local clusters of Tiltepec-Tierra y Libertad and Jaltenango de la Paz, which would provide an interesting example for further research on the reasons behind these patterns.

Official fire management policies in Chiapas are organised according to predefined political regions. As the results of this research show, in practice, actor cooperation is often aligned with these regions. However, there are exceptions, most evident in a combined view of the modularity class analysis and the regional networks shown in Figure 4, aligned with the results of a study of Han et al. (2024) who detected discrepancies between administrative regions and network modularity clusters in a case study of emergency response actors in the United States. In the present case, this comparison demonstrates the existence of a cluster spanning the South of the Valles Zoque region and the Northwest of the Istmo-Costa region, as well as a cluster including the local network of Jaltenengo de la Paz and the municipality of Chicomuselo, outside of the study area. Thus, it should be analysed if the existing official administrative arrangement is not an obstacle to these tight cross-regional subnetworks. Nonetheless, high connectivity within response networks does not automatically indicate effectiveness. This may suggest that preventative measures are ineffective, leading to a greater reliance on emergency responses or a lack of capacity among local institutions to manage fire events independently.

Although network analysis offers valuable insights into inter-agency coordination during wildfire incidents, it is important to acknowledge its limitations. By focusing primarily on the crisis response, the analysis risks privileging moments of intervention over the more routine yet critical practices of fire prevention and mitigation (United Nations Environment Programme [UNEP] 2022). The fact that for this study there was only data on fire suppression available might be indicative of a lack of attention to these essential activities, potentially contributing to the area's relatively high wildfire incidence.

Furthermore, by focusing on formal, institutionalised relationships, there is a danger to overlook informal collaborations, community-led efforts (as the data used in this study are provided by CONANP they may exclude fires extinguished by communities on their own) and indigenous fire stewardship practices that fall outside state-centric frameworks (Huffman 2013; Mistry et al. 2016); in this context, it is important to bear in mind the presence of small rural communities and of the indigenous population mentioned previously. Considering the number of fires documented by Verleye (2024) based on remote sensing, the number recorded in the dataset used here was almost two times lower, which probably has a lot to do with agricultural burning activity, but it might also include at least some wildfires attended by one or several local communities that were not reported to the state and federal authorities.

Political ecology scholarship on fire has highlighted that state-led fire management approaches often marginalise community-based practices and overlook the crucial role of local actors in managing fire (Kull 2002; Sletto 2008). This exclusion may be exacerbated in quantitative network analyses, where the initial lack of representation of certain actors could be incorrectly interpreted as evidence of their limited involvement in fire governance (for instance, in this case, there was no community actor registered in the whole Istmo-Costa region). To address these shortcomings, future research should expand network analysis to include informal and community-based coordination, which will require the collection of grounded data beyond official sources. Additionally, it should consider other aspects of fire management apart from emergency response, such as prescribed burning and the integration of indigenous fire knowledge across different scales of decision-making.

Furthermore, it is important to note that the data used here represent a single wildfire season. Future studies might include data from different years to account for inter-annual variety in fire management efforts, as well as comparisons between different moments of fire season, for example, early season, high season and late season. In addition, it would be interesting to compare fire events with little actor involvement and those with the participation of a great number of different actors, and their impact on firefighting effectiveness. Besides temporal aspects, this kind of analysis would need to consider variables such as the difficulty of the terrain (slopes, access points, kind of vegetation) for firefighting as well as fuel availability and dryness in combination with fire weather measures.

In general, it is important to bear in mind that the present study focused on different approaches of integrating social network and spatial analysis. In this context, it was necessary to stay within a reasonable scope of complexity, which is why the study does not delve into more specialised social network variables. In this context, it is important to note that the network analysis only considers network connections per se, without any further distinctions regarding direction or weight; that is, the relative quantities that characterise network relationships, and which might have altered the results.

5 | Conclusions

This paper aimed at advancing the visual representation and interpretation of spatial social networks in wildfire management, drawing from previous advances in combining geographical research and social network analysis techniques. This was applied to fire management networks in the Southeast of Chiapas, a major wildfire hotspot in Mexico and an area where previous studies had documented the involvement of a multitude of actors participating at the regional and local level.

Mapping networks helped visualising the institutional landscape of fire management, highlighting how various levels of governance—local, municipal and regional—interact in practice. This visualisation served as a starting point for understanding where coordination among various actors is effective and how existing networks may be strengthened or expanded. Recognising these connections is crucial for effective wildfire management, particularly for identifying where additional capacity may be required when fire events surpass the capacity of the local actors.

The methodology of this study allowed the mapping of fire management networks within their geographical context at a new level of complexity, highlighting the relationship between social and relational network spaces, particularly by applying modularity clustering, and imaging the multiscale nature of social networks involved in fire risk governance.

There are several ways that the techniques applied in this work might be advanced in the future, especially by further integrating the development of social network analysis and geographical information system software; in the present case, large parts of the analysis had to be assisted by graphical editing, which complicates the automatic replication of the results of, say, different years and of the application of these approaches at an even higher level of complexity. In addition, the findings regarding the general network patterns in the present paper could be integrated into a deductive study, using inferential statistics to deepen the understanding regarding the influence of different spatial and non-spatial aspects of social network formation.

Moreover, to move from describing and explaining current patterns to understanding them fully and, as a result, arrive at more concrete implications for regional and local decision-makers, the quantitative approach presented here would benefit from an integration with ethnographic fieldwork. This integration with qualitative research could also deepen the analysis on effectiveness of the cooperation between regional actors for successful fire management apart from only focusing on suppression. In turn, while such qualitative studies may offer profound insights on local issues, the study approach presented here might be useful for putting them into a larger regional context.

Acknowledgements

We thank James Millington for his valuable comments on the initial draft of this work, and Luana Wolf Carbajal and Valeria Lara Ocampo for their support with the initial processing of the data. We are grateful for the support of the National Commission of Protected Areas (CONANP) regional office in Tuxtla Gutiérrez, Chiapas, which provided the data used in this research.

Funding

This work was supported by the Dirección General de Asuntos del Personal Académico, Universidad Nacional Autónoma de México, PAPIIT IA300623.

Data Availability Statement

Data will be made available on request.

References

Andris, C. 2016. "Integrating Social Network Data Into GISystems." *International Journal of Geographical Information Science* 30, no. 10: 2009–2031. https://doi.org/10.1080/13658816.2016.1153103.

Andris, C., X. Liu, and J. Ferreira. 2018. "Challenges for Social Flows." *Computers, Environment and Urban Systems* 70: 197–207. https://doi.org/10.1016/j.compenvurbsys.2018.03.008.

Archibald, S., C. E. Lehmann, J. L. Gómez-Dans, and R. A. Bradstock. 2013. "Defining Pyromes and Global Syndromes of Fire Regimes." *Proceedings of the National Academy of Sciences of the United States of America* 110, no. 16: 6442–6447. https://doi.org/10.1073/pnas.1211466110.

Baykal, T. M. 2025. "Performance Assessment of GIS-Based Spatial Clustering Methods in Forest Fire Data." *Natural Hazards* 121: 8445–8477. https://doi.org/10.1007/s11069-025-07135-0.

Bilbao, B., J. Mistry, A. Millán, and A. Berardi. 2019. "Sharing Multiple Perspectives on Burning: Towards a Participatory and Intercultural Fire Management Policy in Venezuela, Brazil, and Guyana." *Fire* 2, no. 3: 39. https://doi.org/10.3390/fire2030039.

Bowman, D., J. Balch, P. Artaxo, et al. 2011. "The Human Dimension of Fire Regimes on Earth." *Journal of Biogeography* 38, no. 12: 2223–2236. https://doi.org/10.1111/j.1365-2699.2011.02595.x.

Bowman, D. M. J. S., C. A. Kolden, J. T. Abatzoglou, F. H. Johnston, G. R. van der Werf, and M. Flannigan. 2020. "Vegetation Fires in the Anthropocene." *Nature Reviews Earth & Environment* 1: 500–515. https://doi.org/10.1038/s43017-020-0085-3.

Comisión Nacional Forestal. 2025. "Manejo del Fuego." https://snif.cnf.gob.mx/incendios/.

Comisión Nacional para el Uso y Conocimiento de la Biodiversidad. 2013. *La Biodiversidad en Chiapas. Estudio de Estado*. Comisión Nacional Para el Uso y Conocimiento de la Biodiversidad y Gobierno del Estado de Chiapas.

Di Gregorio, M., L. Fatorelli, J. Paavola, et al. 2019. "Multi-Level Governance and Power in Climate Change Policy Networks." *Global Environmental Change* 54: 64–77. https://doi.org/10.1016/j.gloenvcha.2018.10.003.

Ellis, T. M., D. M. J. S. Bowman, P. Jain, M. D. Flannigan, and G. J. Williamson. 2021. "Global Increase in Wildfire Risk due to Climate-Driven Declines in Fuel Moisture." *Global Change Biology* 28, no. 4: 1544–1559. https://doi.org/10.1111/gcb.16006.

Evers, C. R. 2020. "Tending the Fire: Wildfire Risk Management at the Interface." Doctoral thesis, Portland State University. https://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=6488&context=open_access_etds.

Expert, P., T. S. Evans, V. D. Blondel, and R. Lambiotte. 2011. "Uncovering Space-Independent Communities in Spatial Networks." *Proceedings of the National Academy of Sciences of the United States of America* 108, no. 19: 7663–7668. https://doi.org/10.1073/pnas.1018962108.

Faas, A. J., A.-L. K. Velez, B. L. Nowell, and T. A. Steelman. 2019. "Methodological Considerations in Pre- and Post-Emergency Network Identification and Data Collection for Disaster Risk Reduction: Lessons From Wildfire Response Networks in the American Northwest." *International Journal of Disaster Risk Reduction* 40: 101260. https://doi.org/10.1016/j.ijdrr.2019.101260.

Faust, K. 2007. "Very Local Structure in Social Networks." *Sociological Methodology* 37, no. 1: 209–256. https://doi.org/10.1111/j.1467-9531.2007.00179.x.

Fischer, A. P., A. Korejwa, J. Koch, et al. 2012. "Using the Forest, People, Fire Agent-Based Social Network Model to Investigate Interactions in Social-Ecological Systems." *Practicing Anthropology* 35, no. 1: 8–13. https://doi.org/10.17730/praa.35.1.w7348256k283t131.

Fleming, C. J., E. B. McCartha, and T. A. Steelman. 2015. "Conflict and Collaboration in Wildfire Management: The Role of Mission Alignment." *Public Administration Review* 75, no. 3: 445–454. https://doi.org/10.1111/puar.12353.

Goldstein, B. E., and W. H. Butler. 2010. "The US Fire Learning Network: Providing a Narrative Framework for Restoring Ecosystems, Professions, and Institutions." *Society & Natural Resources* 23, no. 10: 935–951. https://doi.org/10.1080/08941920903012494.

Grandjean, M. 2015. "GEPHI—Introduction to Network Analysis and Visualization." https://www.martingrandjean.ch/gephi-introduction/.

Guo, D., H. Jin, P. Gao, and X. Zhu. 2018. "Detecting Spatial Community Structure in Movements." *International Journal of Geographical Information Science* 32: 1326–1347. https://doi.org/10.1080/13658816.2018.1434889.

Hamilton, M., A. P. Fischer, and A. Ager. 2019. "A Social-Ecological Network Approach for Understanding Wildfire Risk Governance." *Global Environmental Change* 54: 113–123. https://doi.org/10.1016/j.gloenvcha.2018.11.007.

Han, J., N. Wan, and J. J. Horns. 2024. "Application of Community Detection Methods to Identify Emergency General Surgery–Specific Regional Networks." *JAMA Network Open* 7, no. 10: e2439509. https://doi.org/10.1001/jamanetworkopen.2024.39509.

Hoffman, M., D. Steinley, K. M. Gates, M. J. Prinstein, and M. J. Brusco. 2017. "Detecting Clusters/Communities in Social Networks." *Multivariate Behavioral Research* 53, no. 1: 57–73. https://doi.org/10.1080/00273171.2017.1391682.

Huffman, M. R. 2010. "Community-Based Fire Management at La Sepultura Biosphere Reserve, Chiapas, Mexico." Doctoral thesis, Colorado State University.

Huffman, M. R. 2013. "The Many Elements of Traditional Fire Knowledge: Synthesis, Classification, and Aids to Cross-Cultural Problem Solving in Fire-Dependent Systems Around the World." *Ecology and Society* 18, no. 4: 3. https://doi.org/10.5751/ES-05843-180403.

Instituto Nacional de Estadística y Geografía. 2021. "Censo de Población y Vivienda 2020." https://www.inegi.org.mx/programas/ccpv/2020/.

Jolly, W. M., M. A. Cochrane, P. H. Freeborn, et al. 2015. "Climate-Induced Variations in Global Wildfire Danger From 1979 to 2013." *Nature Communications* 6: 7537. https://doi.org/10.1038/ncomms8537.

Kull, C. A. 2002. "Empowering Pyromaniacs in Madagascar: Ideology and Legitimacy in Community-Based Natural Resource Management." *Development and Change* 33: 57–78. https://doi.org/10.1111/1467-7660.00240.

Le Page, Y., D. Morton, C. Hartin, et al. 2017. "Synergy Between Land Use and Climate Change Increases Future Fire Risk in Amazon Forests." *Earth System Dynamics* 8: 1237–1246. https://doi.org/10.5194/esd-8-1237-2017.

Madrid, L. 2020. "El Desmantelamiento Institucional del Sector Ambiental: Un Balazo en el Pie." Consejo Civil Mexicano para la Silvicultura Sostenible Ciudad de México. https://www.ccmss.org.mx/wp-content/uploads/2020_07_Desmantelamiento-1.pdf.

McCaffrey, S., E. Toman, M. Stidham, and B. Shindler. 2012. "Social Science Research Related to Wildfire Management: An Overview of Recent Findings and Future Research Needs." *International Journal of Wildland Fire* 22, no. 1: 15–24. https://doi.org/10.1071/WF11115.

Mistry, J., B. A. Bilbao, and A. Berardi. 2016. "Community Owned Solutions for Fire Management in Tropical Ecosystems: Case Studies From Indigenous Communities of South America." *Philosophical Transactions of the Royal Society, B: Biological Sciences* 371, no. 1696: 20150174. https://doi.org/10.1098/rstb.2015.0174.

Mistry, J., I. B. Schmidt, L. Eloy, and B. Bilbao. 2019. "New Perspectives in Fire Management in South American Savannas: The Importance of Intercultural Governance." *Ambio* 48, no. 2: 172–179. https://doi.org/10.1007/s13280-018-1054-7.

Moore, P. F. 2019. "Global Wildland Fire Management Research Needs." *Current Forestry Reports* 5, no. 3: 210–225. https://doi.org/10.1007/s40725-019-00099-y.

Neger, C. 2021. "Territorial Configuration of the Social Actors Involved in Fire Management in the Los Tuxtlas Mountains." *BAGE—Bulletin of the Spanish Association of Geography* 90: 1–40. https://doi.org/10.21138/bage.3073.

Neger, C., C. R. Evers, O. Romero, and J. D. Páramo. 2024. "Integrating Social Network Analysis and Cartography: The Case of Fire Management in a Mexican Biosphere Reserve." *International Journal of Cartography* 11: 316–334. https://doi.org/10.1080/23729333.2024.2392213.

Nowell, B., and T. Steelman. 2019. "Beyond ICS: How Should we Govern Complex Disasters in the United States?" *Journal of Homeland Security and Emergency Management* 16, no. 2: 1–5. https://doi.org/10.1515/jhsem-2018-0067.

Owen, G., J. D. McLeod, C. A. Kolden, D. B. Ferguson, and T. J. Brown. 2012. "Wildfire Management and Forecasting Fire Potential: The Roles of Climate Information and Social Networks in the Southwest United States." *Weather, Climate, and Society* 4, no. 2: 90–102. https://doi.org/10.1175/WCAS-D-11-00038.1.

Pimpler, E. 2017. *Spatial Analytics With ArcGIS*. Packt Publishing.

Pompa-García, M., J. J. Camarero, D. A. Rodríguez-Trejo, and D. J. Vega-Nieva. 2018. "Drought and Spatiotemporal Variability of Forest Fires Across Mexico." *Chinese Geographical Science* 28: 25–37. https://doi.org/10.1007/s11769-017-0928-0.

Ponce-Calderón, L., F. Limón, D. Rodríguez-Trejo, et al. 2022. "Fire Management in Pyrobiocultural Landscapes, Chiapas, Mexico." In *Towards Fire-Smart Landscapes*, edited by N. Pasiecznik and J. G. Goldammer, 53–59. Tropenbos International. https://doi.org/10.55515/ABWJ7126.

Silva, J. S., F. Rego, P. Fernandes, and E. Rigolot. 2010. *Towards Integrated Fire Management – Outcomes of the European Project Fire Paradox*. European Forest Institute. https://www.efi.int/publications-bank/towards-integrated-fire-management-outcomes-european-project-fire-paradox.

Sletto, B. 2008. "The Knowledge That Counts: Institutional Identities, Policy Science, and the Conflict Over Fire Management in the Gran Sabana, Venezuela." *World Development* 36, no. 10: 1938–1955. https://doi.org/10.1016/j.worlddev.2008.02.008.

Tedim, F., S. McCaffrey, V. Leone, et al. 2020. "What Can We Do Differently About the Extreme Wildfire Problem: An Overview." In *Extreme Wildfire Events and Disasters: Root Causes and New Management Strategies*, edited by F. Tedim, V. Leone, and T. K. McGee, 233–263. Elsevier. https://doi.org/10.1016/B978-0-12-815721-3.00013-8.

United Nations Environment Programme. 2022. "Spreading Like Wildfire—The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment." https://www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires.

Verleye, E. 2024. "FIRED Mexico Nov 2000–July 2024 [Dataset]." https://scholar.colorado.edu/concern/datasets/5x21th07j.

Wasserman, T. N., and S. E. Mueller. 2023. "Climate Influences on Future Fire Severity: A Synthesis of Climate-Fire Interactions and Impacts on Fire Regimes, High-Severity Fire, and Forests in the Western United States." *Fire Ecology* 19: 43. https://doi.org/10.1186/s42408-023-00200-8.

Wilkin, J., E. Biggs, and A. J. Tatem. 2019. "Measurement of Social Networks for Innovation Within Community Disaster Resilience." *Sustainability* 11, no. 7: 1943. https://doi.org/10.3390/su11071943.

Zhang, G., W. Luo, M. Wu, and L. Ye. 2025. "Exploring Social Interaction Patterns and Drivers in VGI Communities Using a Custom Geovisual Analytics Tool." *Annals of GIS* 31, no. 3: 413–431. https://doi.org/10.1080/19475683.2025.2497026.