Agent-Based Wildfire Evacuation with Spatial Simulation: A Case Study

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ABSTRACT

Fast-moving wildfires pose difficult modeling challenges, including accounting for heterogeneity in individual evacuee behavior and capturing a complex changing system across time dimensions. Here, we employ a NetLogo agent-based model that enables the development of behavioral models for nearest shelter evacuations using origin information. We use GIS shape files (i.e., road network, building blocks etc.) and the spatiotemporal wildfire dynamics (wind speed, direction and possibility of spread) to support our analysis. Our framework is capable of generating various wildfire scenarios that capture the overall evacuation processes. We can use the simulations to demonstrate the feasibility of agent-based models and to compare them under different fire evacuation scenarios.

CCS CONCEPTS

• **Computing methodologies** → **Simulation evaluation**; • **Information systems** → **Geographic information systems**; • **Networks** → **Network performance modeling**; **Network simulations**.

KEYWORDS

wildfire evacuation, agent-based simulation, GIS shapefiles, trajectory data

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1 INTRODUCTION

Catastrophic wildfires pose significant danger and can produce extensive and costly damage. With one in three U.S. homes now located within the wildland urban interface, the risk of catastrophic loss is significant [13]. Most of the largest recent fires have occurred in the U.S. western states where there are high stressed areas experiencing severe drought [7]. California is the state most afflicted by wildfires. The last few wildfire seasons have been particularly damaging. Nearly 2 million acres burned in the 2018 California

wildfire season, culminating in the most destructive season in the state's history. In particular, the 2018 Camp Fire, was the deadliest and most destructive wildfire in the state and the deadliest in the past 100 years nationally [1]. However, the 2020 wildfire season in California has been even worse, over 4 million acres burned as of October of this year.

We adopt an agent-based modeling (ABM) platform to evaluate evacuation performance. ABM's are used in many fields (e.g., see [10–12, 14, 15] and have certain advantages over other methods. First, ABM's focus on individual-level decision-making and how decisions at the most basic level affect larger systems [6]. Theories and ideas that would be infeasible using mathematical models at the system-level can be explored by creating rules for agents to follow [2]. Because the user determines the environment in which the agents move, which can be anything from agents moving on a road network to a virus spreading through a public space, we can easily integrate social and geographical systems [5]. Other advantages include the ability to integrate randomness, the ability to complex behavior between agents, and the ability for an unlimited number of parameters and rules [4, 5]. ABM's are also dynamic, hence they are an excellent tool for use in models in which many factors may simultaneously change over time [6]. Different time scales can be incorporated into the same ABM to accurately capture temporal scales [3].

Agent-based simulation research has contributed in several areas of wildfire research. In [9], the wildfire is treated as a system of systems (SOS) challenge because of the various stakeholders involved. The ABM was used to illustrate changes in interactions between different systems allowing for changes in network configurations. The goal of this work was to find an effective network communication configuration that spanned all agents and could be used to increase the effectiveness of locating and tracking spread of fire. ABMs have been used to describe the interactions between different actors (i.e., directly wildfire, fire crews, machinery, air tools, etc.) during the fire propagation and firefighting process [8] and to study fire suppression [15]. ABMs have also been useful to model human behavior, including using social media to analyze the spatial characteristics of a community in both cyber and physical spaces [12]; to create a data generation framework that includes personal goals, preferences, and needs within a geographical environment [11], and finally, to study location based social networks (LBSN) that can captures both social interactions and real-time locations [10].

2 CONCEPTS AND ARCHITECTURE

We are interested in modeling different evacuation scenarios that take into consideration realistic parameters observed in the true evacuation. Such aspects include fire awareness, departure time,

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and delay, or between finding out and departing during the evacuation. Our study data were collected in Red Cross shelters and online through Qualtrics in the months and weeks following the 2018 Camp Fire. The survey consisted of 51 questions, both multiple choice and short-answer and covered several areas including socio-demographics, evacuation decision-making, evacuation communications, and post-evacuation housing. Between the in-person and usable online surveys, the complete sample size is 397, 34% collected in person, and 66% collected online. Figure 1 shows a visualization of this survey captured at four continuous time intervals. It includes locations of different alert types, density maps to illustrate where each particular alert type of messages is spread and density maps for departed locations.

Using these data, we are interested in examining, for example, if we change the fire spread or road network configuration in our simulation model, how will evacuation outcomes change. Likewise, we are interested in the change in evacuation outcomes when we shift the empirical data. For example, if all evacuees left immediately and did not delay their departure.

Figure 1: Visualization of Empirical Data

Figure 2 demonstrates the chain of events in we aim to simulate. We describe these different elements:

- **Initial Awareness** From our data, we know that residents initially discover about the fire through various means- seeing the fire in person, seeing or smelling smoke, being told in person, receiving an official evacuation order, or finding out by TV, social media, or by a call or text. The awareness

time varies across population, but for the purposes of this exploratory work, we assume the same awareness time for all agents.

- **Departure** We can also observe an evacuee departure time that could be immediate, delayed, or very delayed based on their initial awareness time. We use our survey data to observe the departure times.
- **Evacuation** The evacuation step comprises the agent's journey from their origin to their destination. In our case, the origin s were randomly generated locations from the buildings data. From here, the agent moves to the destination, which is a pre-determined shelter location closest to the agent's origin.

Figure 2: Simulation Structure

Figure 3 illustrates an overview of the model structure. We combine building data, road connectivity, and empirical evacuee data with a simulated fire spread. Agents move along the road network based on their behavioral constraints, escaping to pre-determined shelter locations. Figure 3 also indicates the overall data stream through using ABM (NetLogo). The left-hand side of the figure shows the input data and the right-hand side shows the corresponding outputs (such as, number of commuters, agent trajectories etc.). These parameters can be used to evaluate the evacuation performance and compare results from different fire evacuation scenarios, which is helpful for planning evacuation strategies and tactics.

Figure 3: Model Structure

Figure 4: (a) SouthEast Wind (b) SouthWest Wind (c) NorthEast Wind (d) NorthWest Wind

3 CASE STUDY: WILDFIRE EVACUATION

We simulate the 2018 Camp Fire evacuation that unfolded in the communities of Paradise, Magalia, and Concow in Butte County, California. In this no-notice wildfire event, residents evacuated largely by car but encountered several areas where the fast-moving wildfire impeded their evacuation route, causing them to take different routes or to abandon their personal vehicles.

Simulate Evacuee Behavior The NetLogo model provides an interface to implement evacuee behavior by staggering departure times based on the collected empirical evacuation data. The turtle-commuters are randomly spatially segregated into early, average, and late departure groups. These groups depart at varying time schedules, simulating true evacuee behavior, in which evacuees do not all immediately begin their evacuation upon awareness or notification. All rules for agent behaviors can be predefined into the interface source code such that it controls how each agent behaves under various fire situations. Because of the randomness of when and where people are evacuated in a real-world evacuation case, we pre-implemented rules that allow agents leave at different times and at different random locations.

Simulate Evacuation Process Our basic model is able to simulate different fire scenarios based on the wind direction and possibility of fire spread. The turtle-commuters are able to make dynamic decisions as the fire spreads or blocks their escape routes. Figure 4 shows simulations with 20 commuters that are trying to escape from the fire and arrive at one of the starred locations (shelters). The current model is able to initiate a fire in different locations, spread in different directions and allow commuters to dynamically change their route selections to get to the nearest shelter locations based on the fire. However, our fire model is very rudimentary and includes no fire dynamics.

The road and building networks are imported from GIS shape files where the commuters are created based on the building locations and the connections of vertices (link-agents) in road network is capable of letting commuters travel toward the destinations (shelters). The direction of wind clearly affects the possible escape routes. In Fig. 4 (a), since the wind is in South East direction, most of the commuters are able to travel to destinations because fire only blocked a few roads that do not affect primary escape routes. In the cases of (b), (c), and (d), where many roads are blocked, the majority of evacuees are in high risk of being trapped.

Possible results from simulation The current model in NetLogo can provide multiple forms of results in terms of evaluating the evacuation performances. It is currently capable of tracking the number of people are being evacuated, trapped, and even those who failed to evacuate, a very elementary fire spread over time, and evacuee trajectories for each agent. The top four figures in Fig. 5 shows the burned areas in percentages over time (ticks) which corresponds with four fire scenarios from Fig. 4. The bottom of Fig. 5 shows the percentage of commuters being evacuated over time. The current evacuation model provides options to select the number of evacuees, direction of wind and probability of spread (in percentage). It is also possible to alter the turtle-commuter's departure time, which can provide valuable insight into how the traffic dynamics can change under different departure schedules.

4 CONCLUSIONS AND FUTURE WORK

We developed an exploratory agent-based simulation on wildfire evacuation modeling framework to explore how to create and perform ABM simulations for WUI wildfires. This framework provides users an interface to conveniently set evacuees and wildfire conditions (i.e., probability of spread, fire directions etc.), uses simulations to project evacuation outcomes and from this, we can explore generated datasets, and possibly examine other outcomes that can measure evacuation procedures. We hope to extend this framework to better understand the traffic dynamics of the 2018 Camp Fire. We have supplemented this ABM with empirical behavioral data taken in the months following the event, but this ABM could easily be generalized for other fire-prone locations in the wildland urban interface.

Future work includes completion of all major human behavioral factors into the simulation model, implementation mathematical methods (i.e., Monte-Carlo method) to support decision-making in the model, and using simulated results under possible various fire scenarios and provide corresponding evacuation plans that minimizes the total loss. Additional behavioral factors include mode choice, en-route switching of modes, as well as socio-demographics. We plan to use these socio-demographics applied spatially in a manner in which is realistic of the community of interest, and in the case of the Camp Fire, to interact with various behaviors affecting evacuation.

We made several simplifications and assumptions in constructing the evacuation process, including using a random placement

Figure 5: Corresponding burned areas and successfully evacuated in percentages: (a)(e) SouthEast Wind (b)(f) South West Wind (c)(g) NorthEast Wind (d)(h) NorthWest Wind

of agents and strategically placing fire ignition and shelter points. However, we also hope incorporate the potential wildfire path, population density, and how these factors combine in wildfire evacuation trigger modeling in future iterations. Most importantly, empirical behavioral types will be used to inform the heterogeneity of agent behavior.

To conclude, no-notice wildfires are a significant threat with dire consequences for natural resources and human life, especially for those living in the wildland urban interface. These events have the potential to increase in frequency with climate change and it is important that we make plans as realistic as possible. An ABM combined with empirical data is a powerful tool which can be leveraged to make no-notice wildfire planning more realistic, effective, and in turn reduce the risk of fire in the WUI.

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REFERENCES

- [1] California Department of Forestry and Fire Protection. 2019. CAL FIRE Investigators Determine Cause of the Camp Fire. (California Department of Forestry and Fire Protection. 2019), 7411.
- [2] Robert Axelrod. 1997. *The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration*. NJ: Princeton University Press.
- [3] Michael Batty, Paul Longley, and University College, London. Centre for Advanced Spatial Analysis. 2003. *Advanced Spatial Analysis: The CASA Book of GIS*. ESRI Press. https://books.google.com/books?id=ZcL_REvtgTeC
- [4] Eric Bonabeau. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences* 99, suppl 3 (2002), 7280–7287. <https://doi.org/10.1073/pnas.082080899> arXiv:<https://www.pnas.org/content/99/suppl3/7280.full.pdf>
- [5] Andrew Crooks and Alison Heppenstall. 2012. *Introduction to Agent-Based Modeling*. 85–105 pages. https://doi.org/10.1007/978-90-481-8927-4_5
- [6] Andrew Crooks, Nicolas Malleon, Ed Manley, and Alison Heppenstall. 2019. *Agent-Based Modeling Geographical Information Systems A Practical Primer*. Lecture Notes in Computer Science, Vol. 68. SAGE Publications, New York, NY.
- [7] Philip E. Dennison, Simon C. Brewer, James D. Arnold, and Max A. Moritz. 2014. Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters* 41, 8 (2014), 2928–2933. <https://doi.org/10.1002/2014GL059576>
- [8] Georgy Dorner and Sergey Yarovsky. 2018. Use of Agent-Based Modeling for Wildfire Situations Simulation. In *2018 3rd Russian-Pacific Conference on Computer Technology and Applications (RPC)*. 1–4.
- [9] Mauricio A. Gomez, Yongho Kim, Eric T. Matson, Maria Tolstykh, and Michael Munizzi. 2015. Multi-agent system of systems to monitor wildfires. In *2015 10th System of Systems Engineering Conference (SoSE)*. 262–267.
- [10] Hamid Kavak, Joon-Seok Kim, Andrew Crooks, Dieter Pfoser, Carola Wenk, and Andreas Züfle. 2019. Location-Based Social Simulation. (2019), 218–221. <https://doi.org/10.1145/3340964.3340995>
- [11] Joon-Seok Kim, Hamdi Kavak, Umar Manzoor, Andrew Crooks, Dieter Pfoser, Carola Wenk, and Andreas Züfle. 2019. Simulating Urban Patterns of Life: A Geo-Social Data Generation Framework. (2019), 576–579. <https://doi.org/10.1145/3347146.3359106>
- [12] Xu Lu, Arie Croitoru, Jacek R. Radzikowski, Andrew Crooks, and Anthony Stefanidis. 2013. Comparing the spatial characteristics of corresponding cyber and physical communities: a case study. (11 2013), 11–14. <https://doi.org/10.1145/2536689.2536805>
- [13] Volker C. Radeloff, David P. Hesters, H. Anu Kramer, Miranda H. Mockrin, View ORCID ProfilePatricia M. Alexandre, Avi Bar-Massada, View ORCID ProfileVan Butsic, Todd J. Hawbaker, Sebastián Martinuzzi, Alexandra D. Syphard, , and Susan I. Stewart. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. (2018), 3314–3319. <https://doi.org/10.1073/pnas.1718850115>
- [14] William Rand and Roland T. Rust. 2011. Agent-based modeling in marketing: Guidelines for rigor. *International Journal of Research in Marketing* 28, 3 (2011), 181–193. <https://doi.org/10.1016/j.ijresmar.2011.04.002>
- [15] Xiaolin Hu and Yi Sun. 2007. Agent-based modeling and simulation of wildland fire suppression. In *2007 Winter Simulation Conference*. 1275–1283.