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# Why do we need a national address point database to improve wildfire public safety in the U.S.?

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ABSTRACT

The aim of this paper is to advance understanding of the value of national address point databases in improving wildfire public safety in the U.S. The paper begins with a review of the value of a national address point database in wildfire evacuations. An introduction to address point data in the U.S. is presented by examining two national address point datasets—the National Address Database and the OpenAddresses project. We examine the existing and potential uses of address point data in wildfire evacuation research and practice. Specifically, we cover four primary applications: wildland-urban interface mapping, wildfire evacuation warnings/zoning, wildfire evacuation traffic simulation, and house loss assessment/notification. Based on our review, we find that address point data has the potential to significantly improve these applications and a national address point database can help enhance wildfire public safety in the U.S. Finally, we conclude with a discussion of the challenges of using address point data in wildfire evacuations and future research directions. This review proposes an agenda for further research on the potential use of address point data in wildfire evacuation applications and sheds light on the development and applications of the two national address point database projects.

## 1. Introduction

In recent years, there has been a significant increase in the number of individuals opting to live in the fire-prone areas in the U.S. [1–4]. The wildland-urban interface (WUI) is defined as the areas where human residences and wildland vegetation meet or intermix [5–7]. At the same time, large, destructive fires have become more common in the American West [8]. Wildfire poses a significant risk to life and property in the WUI [9], and longer fire seasons have resulted in significant loss of life and property in these areas. For example, according to the California Department of Forestry and Fire Protection (CAL FIRE), the Tubbs Fire in October 2017 burned 5636 structures and caused 22 deaths in Northern California, and the Camp Fire in November 2018 destroyed 18,804 structures and killed 88 people in Butte County, California, making this event the most destructive wildfire in California history [10]. Despite the increasing risks and vulnerability posed by living in the WUI, these areas continue to experience significant growth. The question of how human populations can better coexist with wildfire risk has attracted significant research attention [11,12].

When a wildfire moves towards communities and becomes a threat to residents, incident commanders (ICs) issue protective action recommendations (PARs) to the threatened population to maximize public safety [13]. Common protective actions recommended in the U.S. include strategies such as evacuation and shelter-in-refuge whereas other countries such as Australia may recommend preparing and defending a home when the right conditions are met [14–16]. Prior studies reveal that ICs need to take into account a wide range of factors (e.g., wildfire spread speed and direction, the location of the threatened population, evacuation behaviors, and the evacuation route systems (ERS)) in order to make effective PARs in wildfires [16–18].

The rapid development of modern spatial data acquisition techniques such as GPS data and high-resolution remote sensing allows for the development of new datasets with high spatial and/or temporal resolution for a variety of new applications. Address data have been an integral component of a wide range of surveys, and textual address data

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can be conveniently converted to geographic points through geocoding [19]. Geocoded address data have been used in many applications such as public health [20,21], transportation [22], and crime studies [23]. In evacuation studies, household surveys have also been widely used to study evacuation behavior [24–29].

Address point data has both address and location (a geographic point) information, and the spatial accuracy of this data is generally better than that of those points derived from street geocoding [30]. In Australia, the Public Sector Mapping Agencies (PSMA) established a Geocoded National Address File (G-NAF) and provides it to the public as open data to support various applications [31]. This dataset has been successfully used by IBM Research Australia to build modern wildfire evacuation systems [32]. However, a complete national address point dataset is lacking in the U.S., which has become a bottleneck for evacuation researchers and practitioners to build more efficient and effective wildfire evacuations systems and better protect life and property. This was highlighted by the U.S. Department of Transportation (DOT) who identified the need for accurate address point data in disaster management [33].

The focus of this paper is the application of address point data in wildfire evacuation planning and management, and the objectives are two-fold. First, we aim to help wildfire evacuation researchers and practitioners develop a better understanding of the current state of the national address point databases and the potential value of this dataset in wildfire evacuation research and practice. Second, this review also aims to provide feedback to developers of national address point databases from the perspective of wildfire evacuation applications. The ultimate goal is to promote the use of this new dataset in wildfire evacuation research and practice and build better wildfire evacuation systems to improve public safety.

First, this article provides a brief introduction to the current state of two national address point datasets in the U.S. Second, this paper identifies the need for more accurate address point data in wildfire evacuations and provides a review of the uses of this dataset in wildfire evacuation research and practice. Lastly, we give a discussion of the challenges of using this dataset in wildfire evacuations and provide relevant suggestions, which can shed light on the development, maintenance, distribution, and application of national address point datasets in the U.S. This paper also proposes an agenda for further research on the potential use of national address point databases in wildfire evacuation applications.

## 2. Address point data in the U.S.

An address point is composed of two parts—the textual address name and the point geometry that georeferences the location of the address on the Earth's surface. Address point data typically include all the buildings with addresses and are usually derived by extracting the structure locations from a high-resolution ortho-image map. In the U.S., the address point data are developed and maintained by local authorities (e.g., the GIS department of each county). The pressing needs for consistent address point data require collaboration across different government jurisdictions and levels to develop a national address point database. In the U.S., the DOT has been working with its partners to compile and develop a public national address database (NAD) [34]. USDOT has defined a data schema to manage all the address point data in the nation. The schema includes many important attributes for each record including street name, address number, county, state, zip code, geographic coordinates, National Grid coordinates, address type, address source, address authority, and updated/effective/expiration date. USDOT has received address data from 23 state partners and transformed the data into the NAD schema. Moreover, USDOT has published a version of the NAD as an ESRI geodatabase format file for public use in February 2018 [34]. This dataset includes a total of 33,697,845 address point records.

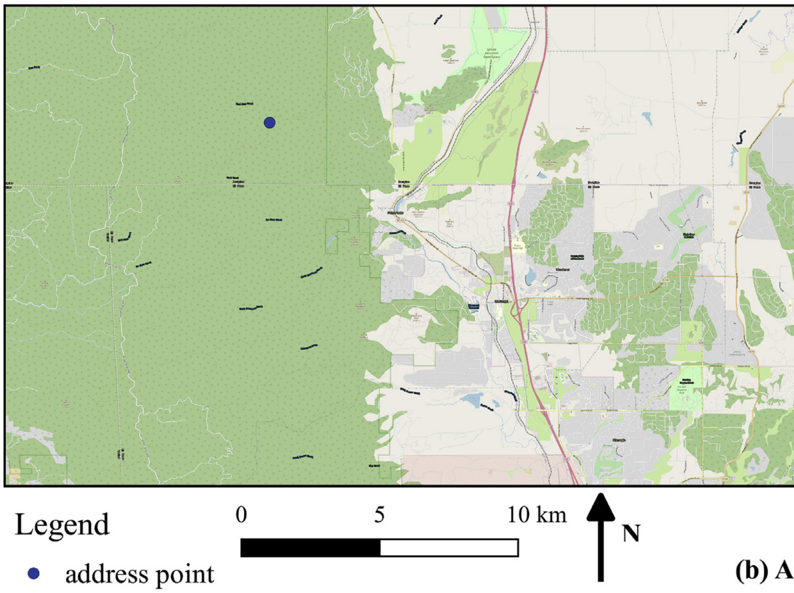
Equally important to the development of the NAD in the U.S. are the inputs from subject matter experts. The NAD can serve as the geospatial infrastructure for many different disciplines and a variety of applications. DOT states that the NAD can be used for a range of government services such as mail delivery, permitting, the Next Generation 9-1-1 system [35], and school siting [34]. In addition to these applications, the database has potential in many other applications. For example, address point data could be used to compute each household's accessibility to health care facilities or other health resources [36]. This fine-grain measurement is powerful when used in studies that examine associations at different census unit levels. The past few years have witnessed a great many accessibility studies at different census unit levels such as census tract, census block, and block group [37–39].

Another national address point dataset is available in a global open address data initiative—the OpenAddresses project [33]. This project is hosted on GitHub, and it has about 128 contributors as of November 2018. The entire data repository is organized by country, and the U.S. dataset is organized by state. The contributors can share the address point data in the repository according to some common standards. All the address point data are in separate comma-separated values (CSV) files. Each record includes the following important attributes: geographic coordinates, street name, address number, unit information, city, district, postcode, and ID. Users can download these files and convert them to GIS format files using relevant GIS software packages. The project website documents the statistics of the data in each country and allows everyone to download the data directly with no cost [40]. According to the published statistics on data coverage, the OpenAddresses project covers 65.0% of the land area and 81.6% of the population (about 262,535,000 people) in the U.S. The address point data from this project have the following issues: 1) overlapping source data; 2) lacking feature-level metadata; 3) non-authoritative data (e.g., data gathered from non-government agencies); and 4) data lacking essential address information (e.g., data only including geographic points and not the address information) [33]. These issues could restrict the direct use of this dataset in many applications.

We use one structure located in the Pike National Forest to the west of Larkspur, Colorado in the U.S. as an example to demonstrate the composition of an address point. As shown in Fig. 1, the attributes of this structure from the OpenAddresses project only include the basic address information and the geographic coordinates of the point, while the attributes from the NAD project have more information. Note that the above-mentioned two national address point database initiatives are still ongoing and not complete, and a significant amount of data collection and research remains to be conducted before these national address point datasets can efficiently and effectively be used in various applications. Research on the applications of address point data (especially a national address point database) would not only advance research in many fields but also provide feedback for the designers and developers of these two address point database initiatives. This work aims to identify the potential value of address point data (especially a national address point database) in wildfire evacuation research and practice.

## 3. Applications of address point data in wildfire evacuation

Address point data have a wide range of applications in different fields. In this article, we restrict our discussion on the applications of address point data in wildfire evacuation. Note that this examination is not exhaustive but covers the important inquires of research in this area. Specifically, four primary topics are included: WUI mapping, wildfire evacuation warning and zoning, wildfire evacuation traffic simulation, and house loss assessment and notification. We provide a review of the important literature in each subfield and list the existing and potential uses of address point data in different applications and how a national address point database can facilitate wildfire evacuation management and planning.




**(a) Attributes from OpenAddresses**

| ID | Field Name | Value |
|---|---|---|
| 1 | X | -104.9656293 |
| 2 | Y | 39.1498433 |
| 3 | lon | -104.9656293 |
| 4 | lat | 39.1498433 |
| 5 | number | 14041 |
| 6 | street | FOREST LN |
| 7 | unit | |
| 8 | city | LARKSPUR |
| 9 | district | |
| 10 | region | |
| 11 | postcode | 80118 |
| 12 | id | |
| 13 | hash | 87cdc57448733084 |
| 14 | filename | douglas |
| 15 | statename | co |

**(b) Attributes from the NAD project**

| ID | Field Name | Value | ID | Field Name | Value | ID | Field Name | Value |
|---|---|---|---|---|---|---|---|---|
| 1 | X | -11684720.4 | 16 | StN_PreTyp | | 31 | Addtl_Loc | |
| 2 | Y | 4743158.125 | 17 | StN_PreSep | | 32 | Milepost | |
| 3 | OBJECTID | 18325621 | 18 | StreetName | Forest | 33 | Longitude | -104.9656193 |
| 4 | State | CO | 19 | StN_PosTyp | Lane | 34 | Latitude | 39.14983694 |
| 5 | County | Douglas | 20 | StN_PosDir | | 35 | NatGrid_Co | 13SED0297033404 |
| 6 | Inc_Muni | LARKSPUR | 21 | StN_PosMod | | 36 | GUID | {D1F2A7E8-DCF5-40A0-A4E4-E82D5208F438} |
| 7 | Uninc_Comm | | 22 | AddNum_Pre | | 37 | Addr_Type | Unknown |
| 8 | Nbrhd_Comm | | 23 | Add_Number | 14041 | 38 | Placement | Unknown |
| 9 | Post_Comm | | 24 | AddNum_Suf | | 39 | Source | Colorado OIT GIS |
| 10 | Zip_Code | 80118 | 25 | LandmkPart | | 40 | AddAuth | Douglas |
| 11 | Plus_4 | | 26 | LandmkName | | 41 | UniqWithin | |
| 12 | Bulk_Zip | | 27 | Building | | 42 | LastUpdate | 5/18/2017 |
| 13 | Bulk_Plus4 | | 28 | Floor | | 43 | Effective | |
| 14 | StN_PreMod | | 29 | Unit | | 44 | Expired | |
| 15 | StN_PreDir | | 30 | Room | | | | |

**Fig. 1.** An example of the address point data from the OpenAddresses and NAD project.

### 3.1. *WUI mapping*

The United States Department of Agriculture Forest Service defines in the Federal Register three categories of WUI communities—interface community, intermix community, and occluded community and gives the detailed criteria for each WUI type [41]. This classification scheme is based on housing density and the spatial configurations of houses in relation to the wildland area. Specifically, an interface community is defined as the case that the structures directly abut wildland fuels and the development density is at least 3 structures per hectare (6.17 structures per $km^2$); the housing density for an intermix community is equal to or larger than 1 structure per 40 acres; an occluded community has the same housing density as an interface community but its area is smaller than 1000 acres [41]. The detailed criteria for defining different types of WUI communities are listed in Table 1 [41]. Note that WUI can be defined by housing density or population density, and WUI mapping can also be accomplished differently.

A large body of research has been conducted on WUI mapping in the U.S. and in many other countries throughout the past two decades. For example, Radeloff et al. [6] did some seminal work on national WUI mapping in the U.S. based on the definition of WUI in the Federal Register. Specifically, they employed the national census block data from U.S. Census and the U.S. Geological Survey (USGS) National Land Cover Data (NLCD) to calculate and map the interface and intermix WUI communities in the conterminous U.S. based on the housing density defined in the Federal Register [6]. For the intermix WUI communities, Radeloff et al. [6] used a threshold of 50% vegetation to select out the census blocks; as for interface communities, they used buffer analysis to select the census blocks that fall within 2.4 km of a large heavily vegetated area (> 75% vegetation and larger than 5 $km^2$) [6]. The results of this national WUI mapping endeavor are published as open data and have been used in a variety of wildfire management applications, e.g., wildfire risk assessment [42].

Subsequent research has started to use other ancillary data to further improve WUI mapping. For example, Theobald and Romme [4] took into account several more aspects such as community protection zone, fire severity, and fire regimes and incorporated more data (e.g, the US Department of Agriculture's FUELMAN dataset) to map out the WUI (including both interface and intermix WUI areas) in the U.S. Furthermore, Theobald and Romme [4] also employed the Spatially

**Table 1**
The criteria for different types of WUI community defined in the Federal Register.

| WUI Type | Criteria | |
|---|---|---|
| | Housing Density | Population Density |
| Interface | 3 or more structures per acre (4,047 $m^2$) | 250 or more people per square mile (2.59 $km^2$) |
| Intermix | Ranges from structures very close together to 1 structure per 40 acres (161,874 $m^2$) | 28-250 people per square mile (2.59 $km^2$) |
| Occluded | Similar to those in the interface community but the area is smaller than 1000 acres (4.047 $km^2$) in size. | N/A |

Explicit Regional Growth Model to develop projected WUI patterns for 2030 and estimated WUI expansion. Although the census block data were used as the population data in this study, a dasymetric mapping technique was used to convert the polygon census block data into a population raster dataset based on road density [4].

Dasymetric mapping is an areal interpolation technique in GIS that leverages ancillary data to map a phenomenon in meaningful spatial units [43–45]. The existing methods for mapping the WUI in the U.S. largely reply on the population or housing density data at the census block level [4,6]. Address point data have the potential to improve WUI mapping either through direct measurement of household density in the WUI, or through dasymetric techniques that model population density through a combination of census and address point data. Thus, compared with the current coarse-grained methods, address point data will enable researchers to map the WUI more precisely. Recent studies have started to use address point data to further improve WUI mapping [46]. Platt [46] also pointed out that structure location data are often incomplete and expensive to compile in WUI mapping. Thus, a national address point database will significantly facilitate more precise national WUI mapping in the U.S. and improve the accuracy of a variety of applications including wildfire evacuation planning and wildfire hazard mitigation that rely on WUI maps.

### 3.2. *Wildfire evacuation warning and zoning*

When a wildfire approaches residences and becomes a threat to the WUI residents, a PAR will be issued by ICs to protect life and property. Note that protective actions vary by hazard type, and the primary protective actions in wildfires include evacuation and shelter-in-place (shelter-in-refuge) in the U.S. [14,16]. When ICs send out a warning, they need to specify what group should take what protective action and when to take it [17,47,48]. Protective action decision-making in wildfires is a challenging task for ICs because they need to consider many factors such as fire spread, population distribution, and evacuation traffic [14,17]. Based on several decades' evacuation warning research, Lindell and Perry [49] proposed a protective action decision model that has been widely used in evacuation studies in the past few years. The past few decades have witnessed a large body of research on household evacuation behaviors [24,28,50], and these behavioral studies could be utilized to model household evacuation behaviors and facilitate wildfire evacuation modeling in a more systematic way if a national address point database is available. The evacuation models based on the findings from these behavioral studies can better mimic the evacuation process and help improve evacuation timing and warning. In addition, household surveys in evacuation studies align with address point data geographically with regard to spatial units, which makes a strong argument to develop and maintain a national address point database in the U.S. from the perspective of evacuation research. With a national address point database, evacuation modelers can readily incorporate the evacuation behaviors from household surveys into evacuation models to improve evacuation warning.

One important line of research to improve wildfire evacuation warning is wildfire evacuation triggers. Warning triggers can be considered as a mechanism that takes into account factors such as the hazard, the threatened population, and the built environment (e.g., the ERS) to improve decisions related to who to warn, when to warn them, and determine what the appropriate PAR should be given the situation [17]. Prominent features such as river, road, and ridge line are widely used as trigger points in wildfire evacuations, and when a fire crosses a trigger point, a PAR will be issued to the threatened residents [51]. Computerized modeling of wildfire evacuation triggers was initiated by Cova et al. [52], and fire spread modeling and GIS were used to set triggers. Trigger modeling is based on the raster model—a GIS data model that uses a regular grid to cover the space [53]. Dennison, Cova, and Moritz [54] formulated the whole trigger model into a three-step procedure: 1) performing fire spread modeling to derive fire spread rates in eight directions for every raster cell; 2) constructing a fire travel time network by connecting orthogonally and diagonally adjacent

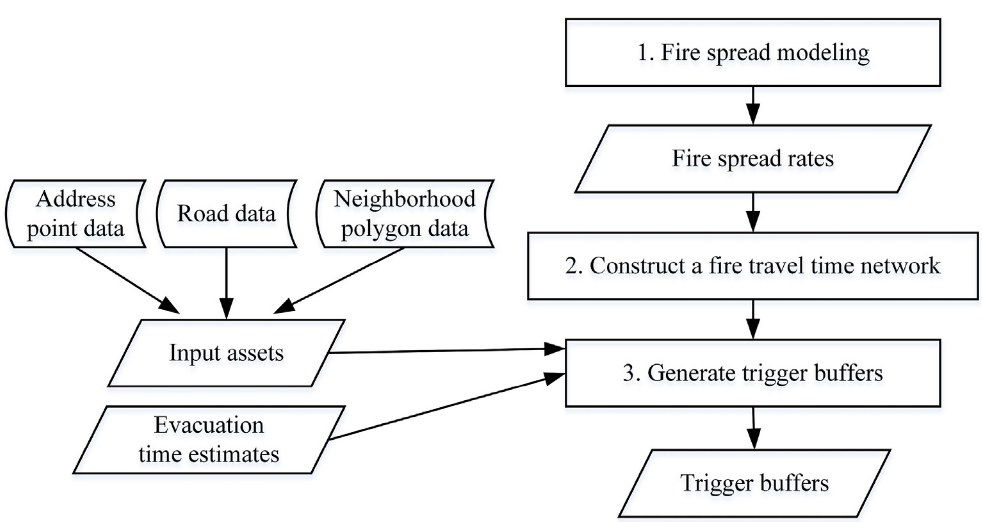



**Fig. 2.** The workflow of trigger modeling.

raster cells; 3) reversing the directions of the arcs in the network and using the shortest path algorithm to traverse the network from the input asset cells to generate a trigger buffer for a given input time *T*. The workflow of trigger modeling is shown in Fig. 2. Note that the input asset in this context could be some real-world assets such as a house or a community, where delineation of individual houses or the edge of a community could be improved by address point data. The input time *T* for trigger modeling is based on the evacuees' lead time and can be estimated by using evacuation traffic simulation [55]. Relevant research has shown that wildfire evacuation trigger modeling has a wide range of applications such as protecting firefighters [52,56] and pedestrians [57] in the wildland, improving community evacuation planning [54,58] and evacuation timing and warning [55], staging household evacuation warnings [59], and facilitating communications during wildfire evacuations [60].

The value of address point data in wildfire evacuation warning is that they can be used to build household-level evacuation warning systems. For example, Li, Cova, and Dennison [59] used the centroids of residential parcels as the input for trigger modeling and used wildfire simulation to stage evacuation warnings at the household level. Address point data will be more accurate for trigger modeling and have a great value in building better evacuation warning systems in wildfires and other types of hazards. A standardized national address point database will be essential in building a centralized evacuation warning system for those hazards that impact a large geographic area. It can also be employed to build more intelligent geotargeted warning systems [61]. For example, we can use address point data to issue tailored protective action warnings to specific at-risk households, thus recommending actions such as advising a household to evacuate, recommending they seek shelter at a designated safe-zone, or encouraging them not to evacuate if they are outside the risk zone. This can help reduce issues related to over-evacuation, which can be dangerous especially in situations where traffic impedes the ability of residents to safely and quickly evacuate. Additionally, there is potential for these warnings to specify the safest route for evacuating and indicating the closest shelter option.

Note that trigger modeling is based on fire spread rates derived from fire spread modeling, and wildfire spread simulation has also been widely used to build coupled models to facilitate wildfire evacuation in the past few years [32,55]. In the U.S., the open data initiative LANDFIRE provides various types of national GIS datasets for wildfire research [62]. Specifically, the LANDFIRE products that can be used for fires spread and trigger modeling are summarized in Table 2. Note the all the LANDFIRE products are at 30 m cell resolution [62]. Evacuation modelers could use these national datasets to implement a wildfire simulation system that will work for the entire U.S. In this regard, a national address point database could be a great complement to the LANDFIRE project and will allow evacuation researchers and practitioners to implement the trigger model or coupled evacuation models at the household level for any geographic area of any size in the U.S. to improve wildfire evacuation warning.

When the ICs send out protective action warnings, it is a common practice that they divide the risk area into a set of zones and stage the warnings with the progression of the fire [63]. Evacuation zoning is closely related to evacuation warning but still remains an under-researched subfield in evacuation studies. Note that evacuation zoning mechanisms could vary with hazard type and intensity [64]. For example, Wilmot and Meduri [65] presented a methodology to establish hurricane evacuation zones based on a set of widely recognized principles such as the zones should be areas of uniform elevation and should not overlap with each other. Specifically, they used primary roads to divide zip code zones into subareas and employed these subareas as the building blocks to construct hurricane evacuation zones based on elevation [65].

**Table 2**
The primary LANDFIRE products for wildfire spread modeling.

| LANDFIRE Products | Description |
|---|---|
| Topography | Aspect, elevation, and slope |
| Surface Fuel model | 13 Anderson FBFMs, 40 Scott and Burgan FBFMs |
| Canopy Fuel | Forest canopy cover, height, bulk density, and base height |

As for wildfires, little research has been done with regard to the mechanisms or principles of evacuation zone delineation. The most relevant research to date is a study that applies trigger modeling at the household level and employs fire spread simulation to construct evacuation warning zones by aggregating household-level warnings [59]. Since wildfire evacuation zones are usually smaller than hurricane evacuation zones, address points can be potentially used as the building blocks to construct evacuation zones in wildfires and stage warnings at the household level. However, each county/state in the U.S. currently maintains its address point data, which may cause inconvenience in data compilation when a wildfire spans multiple jurisdictions and impacts multiple counties or states because conflating incompatible data sets can take a significant amount of time and effort. Thus, a well-maintained national address point database will be valuable when a wildfire evacuation crosses jurisdictional boundaries in the U.S.

In addition to identifying the detailed locations of the threatened population, address point data can also be leveraged to more efficiently identify potential evacuation shelters during wildfire evacuation. Shelter information is also an integral part of a warning message and plays a significant role in evacuation warning [47,48]. Note that different types of addresses can be included in the address point data, and some address points such as schools and stadiums can be used as evacuation shelters. Although the data in the two above-mentioned national address point databases do not include detailed information on the address such as structure type and capacity, other types of GIS data such as point of interest (POI) data can be leveraged to enrich the address point data and identify the structures that can be used as shelters in wildfire evacuation.

Furthermore, address point data can also be employed to develop relevant systems for the re-entry process. Reentry of the evacuated residents to the evacuated areas is common in many evacuations and is a challenge for emergency managers [66]. Early reentry could cause deaths because the evacuated areas are not safe yet. Delays in issuing reentry messages could have an adverse effect on the residents' compliance with future evacuation orders and adversely affect the local economy [67]. Although wildfire reentry studies are lacking, relevant studies on hurricane reentry have found the difficulty of communicating the reentry messages to the evacuees in a timely and accurate manner, which can be made increasingly difficult in cases where evacuees are scattered across a large geographic area [68]. With this regard, address point data can be used to develop relevant information systems for the reentry process in wildfires, which can facilitate reentry communications, regardless of where evacuees are located, and improve public safety.

### 3.3. Wildfire evacuation traffic simulation

Since the household vehicle ownership rate is high in the U.S., a vehicle is the primary travel mode in wildfire evacuations [69,70]. Thus, managing evacuation traffic plays a significant role in maximizing public safety in wildfires. Since it is impractical to do evacuation experiments to study evacuation traffic, we need to rely on computer simulation tools. In the past few decades, traffic simulation has grown in popularity in evacuation modeling and simulation [71–73]. Specifically, based on the four-step transportation planning procedure, Southworth [69] formulated regional evacuation planning into a five-step process: trip generation, trip departure time, trip destination, route selection, and plan setup and analysis. Once the evacuation zones are delineated [74,75], one key step in evacuation trip generation is to determine evacuee population distribution [29,69]. Note that evacuee population distribution varies by time of day, and it is expensive and challenging to derive detailed spatio-temporal data on the evacuee population distribution [69,76].

In hurricane evacuation simulations, traffic analysis zones are typically used to generate evacuation travel demand, while house location data have been widely used in wildfire evacuation modeling [32,55,77,78]. Note that traffic analysis zones are usually very large and cannot be directly used in wildfire evacuations because the boundaries of smaller-scale evacuations cannot be precisely delimited. It was cumbersome and time-consuming to compile the house location data in those early studies in the U.S. [77,78], while it was relatively simple to code the road network for traffic simulation because U.S. Census maintains and hosts a national road dataset through its TIGER project [79]. One advantage of using address point data to generate evacuation travel demand is that we can model the detailed spatial distribution of the evacuee population. Most address points are single family houses in the WUI. Thus, technically speaking, if we have the detailed household vehicle ownership data, we could model evacuation traffic with a very high accuracy. However, it would be costly to compile and maintain car ownership data for every household. In many cases, we would need to rely on household surveys to compile and produce this data. The American Community Survey (ACS) has vehicle ownership data for many geographic areas in the U.S., which can be leveraged to systematically generate evacuation travel demand at the household level in evacuation modeling [55].

Evacuation traffic simulation can be used to facilitate wildfire evacuation in several ways. Early studies on evacuation modeling focus on using evacuation traffic simulation to derive the total network clearance time needed by the evacuees [80–82]. Han, Yuan, and Urbanik [83] proposed a four-tier measures of effectiveness (MOEs) framework for evacuation: 1) evacuation time; 2) individual travel time and exposure; 3) time-based risk and evacuation exposure; and 4) time-space-based risk and evacuation exposure. Traffic simulation can be divided into three categories based on the level of detail: macroscopic, mesoscopic, and microscopic traffic simulations [69]. Compared with hurricanes, wildfires usually occur in a smaller geographic area and threatens fewer people. Thus, it is computationally feasible to perform wildfire evacuation modeling at a fine-grained level, and microscopic traffic simulation has grown in popularity in wildfire evacuation modeling [32,55,77]. More importantly, microscopic traffic simulation enables evacuation researchers and practitioners to derive time-space-based risk and evacuation exposure for the evacuees when it is coupled with a wildfire spread model [32,55]. With the recent development of evacuation modeling, the researchers in this field have reached a consensus that interdisciplinary collaboration is the key to better modeling the evacuation process [17,64,84].

A significant amount of research has been conducted on wildfire evacuation modeling in the past few decades. Early studies on wildfire evacuation modeling focus on using evacuation traffic simulation to identify those vulnerable WUI communities that have a high housing density but insufficient road capacity for egress [77,78]. This line of research examines housing density and the capacity of the ERS and can shed light on future housing development and evacuation planning in the WUI [9]. Recent studies on wildfire evacuation modeling have started to adopt an interdisciplinary approach that focuses on model coupling and integration [32,55,85]. Specifically, Beloglazov et al. [32] coupled microscopic traffic simulation, trigger, and fire spread models within a cloud computing framework to study space-time evacuation risk in Australian wildfires. This coupled model was later applied to examine evacuation shelter selection in wildfires [85]. Another study in the U.S. coupled fire spread, traffic simulation, and trigger models to set triggers and improve wildfire evacuation timing and warning [55]. Although detailed road information (e.g., speed limit and number of lanes) still needs to be compiled from local transportation authorities in the U.S., a national road dataset can be downloaded from the U.S. Census TIGER project for evacuation traffic simulation. However, evacuation modelers in the U.S. currently need to spend a significant amount of time collecting address point data or parcel data from each city/county government to generate travel demand in wildfire evacuation traffic simulation. Data inconsistency issues will also arise when several counties or states are involved in a wildfire evacuation. Evacuation modelers cannot build an evacuation model like the one developed by IBM Research Australia [32] that can be used for any area in the U.S. without a national address point database. Thus, a national address point database can serve as the cyberinfrastructure for evacuation traffic simulation in wildfires or other hazards and significantly facilitate wildfire evacuation decision-making.

### *3.4. House loss assessment/notification*

During wildfire evacuations, evacuees will have a variety of information needs such as information pertaining to who needs to evacuate, when they need to leave, what are the locations of shelters or other safe destinations, and house loss [24]. Note that evacuees and non-evacuees could have different information needs in different phases of the evacuation [86]. One important information need the evacuees are particularly concerned with after the event is the status of their house [27]. The evacuees want to know the effects of the fire on their houses during and after their evacuation. Thus, it is important that public safety officials deliver this information in an accurate and timely manner. There are many different channels the officials can use to disseminate house damage information, e.g., hotlines, mass media, and website. However, some channels such as media reports may cause inaccuracies during the information dissemination process or take a long time to deliver the information to the evacuees [27]. Maps have a huge advantage in locating the house accurately, and a Web GIS can deliver the information in an accurate and timely manner.

Another important application of address point data is house loss assessment and notification in wildfires. The principles of this application are simple and straightforward. The address point data can serve as a layer in a Web GIS for house loss notification. The high accuracy of address point data makes it convenient for the evacuees to locate their house by navigating the web map. The evacuees can also use the address as the input and locate their house through address matching or geocoding in the Web GIS. Address point data can also play a significant role in house loss assessment. The high accuracy enables the public safety practitioners to use aerial photographs derived from satellites, planes, or drones to assess house damage in a timely way. In addition, the information can be readily entered into the house loss notification system. Thus, address point data can play a significant role in the whole information flow. Recently, some counties and states have started to use address point data in house loss assessment and notification systems in the U.S. However, without a consistent national address point database, it remains a challenge to build house loss notification/assessment systems that can be used when a wildfire crosses several jurisdictions. A national address point database can help build more efficient and effective house loss assessment and notification systems for wildfires and many other types of hazards in the U.S.

## 4. Examples

In this section, we use some real-world examples to illustrate the uses of address point data in wildfire evacuation practice to complement the above discussion on wildfire evacuation research. Specifically, we focus on the uses of address point data in wildfire evacuation zoning/warning and house loss assessment/notification.

### *4.1. Wildfire evacuation zoning and warning*

The first example is the use of address point data in wildfire evacuation zoning and warning. Specifically, we use the 2018 Vineyard

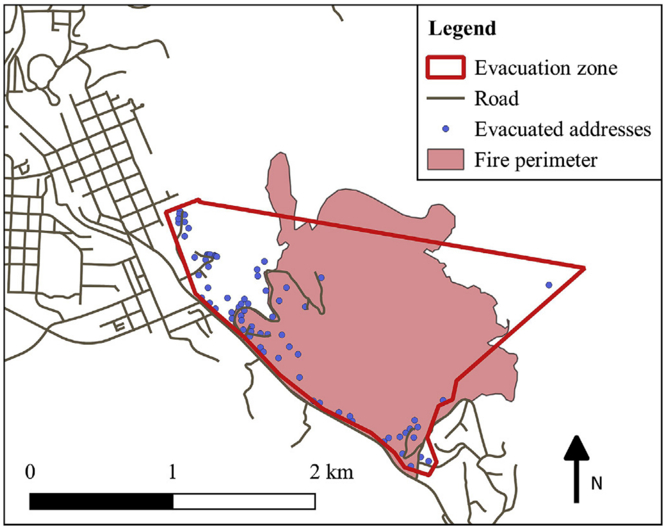



**Fig. 3.** The address point data used in the evacuation maps in the Vineyard Fire.

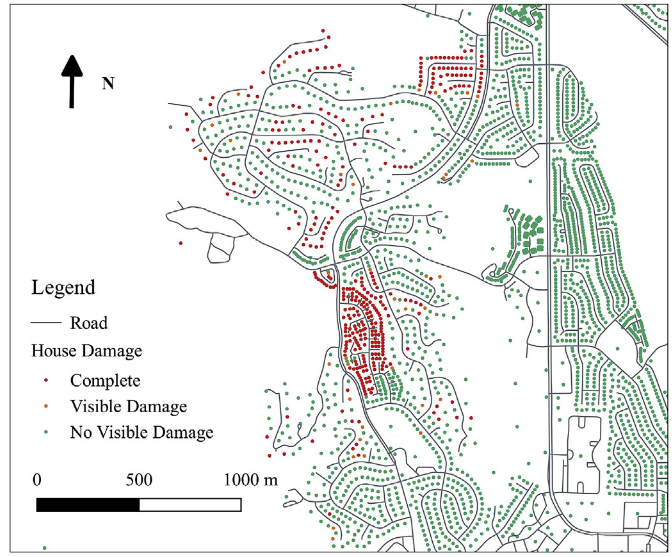



**Fig. 4.** The house loss assessment map in the Waldo Canyon Fire.

Fire in South Dakota as an example. The Vineyard fire began on August 11 near Hot Springs, South Dakota. Hot Springs is a small city with a population of 3711 in Fall River County, South Dakota. This fire resulted in the evacuation of dozens of households. The local Office of Emergency Management released relevant evacuation maps to facilitate evacuation warnings during this fire through their county website and Facebook account. Note that the Fall River County Department of GIS maintains an address point dataset for the whole county, and this dataset was used to overlay the warning zones in the evacuation maps to help residents better identify whether they fall within the warning zone or not. As shown in Fig. 3, each individual point reflects the address point used in evacuation zone mapping. The residences within or close to the fire perimeter were notified to evacuate first, and the residents in eastern Hot Springs were notified to evacuate with the progression of the fire. The residents can easily identify the evacuation warning zone they fall within and what protective action to take during the evacuation through the evacuation maps and relevant warning messages published on the county's website and its social media pages (e.g., Twitter, Facebook). Relevant research has shown that well-designed maps can facilitate emergency warning when used with text warnings [87,88]. Furthermore, address point data can also be used in a Web GIS to enable the residents to better interact with the maps and get the accurate evacuation order. Another upside of using address point data is that the technical support teams can readily compute a series of attributes for the delineated evacuation zones such as the total number of households (i.e., address point), the number of vehicles (estimated based on the average vehicle occupancy rate), and the total property value within each zone. This information can play a significant role in evacuation decision-making. However, it is important to note that the ability to use Web GIS is dependent on the availability of the Internet as well as electricity to charge cell phones, laptops, tablets, and other devices. Therefore, given this limitation, multiple communication platforms, such as reverse 911, television, radio, and face-to-face communication are still critical and necessary to ensure all populations receive warnings [89].

This evacuation is representative of small-scale wildfire evacuations in the U.S. It is within one county and is managed by the county IC. Since each county manages its own spatial data in the U.S., evacuation practice can vary by county. Despite the great value of address point data in evacuation practice, there is no consensus or a standardized procedure on how to use it in wildfire evacuation practice. Given that the format for address point data can also vary from one county to another, a consistent national address point database will significantly facilitate building standardized procedures or system for wildfire evacuation, especially in cases where evacuations span across different political boundaries such as county and state lines. As for wildfire evacuation systems, each state can build and maintain a centralized evacuation system and use it for local evacuations by collaborating with the local government agencies. This could significantly reduce the cost of maintaining evacuation systems at the local level and help build more effective and efficient wildfire evacuation systems.

### 4.2. House loss assessment/notification in recent wildfires

House loss information is one of the key information needs during wildfire evacuation, and the fine-grain address point data can be used as the basis for house loss assessment and notification systems. One example is the house loss assessment for the Waldo Canyon Fire in Colorado Springs, Colorado in 2012. This fire started on June 23 and was fully contained on July 10. This fire triggered the evacuation of thousands of people and resulted in two fatalities. Moreover, this fire destroyed 347 homes and damaged many others [90]. After this fire, a house loss assessment was conducted by the city government, and address point data were used for house loss mapping. As shown in Fig. 4, the houses (i.e., address points) were categorized into three types: complete (total loss), visible damage, and no visible damage. Specifically, the information technology department of Colorado Springs used high-resolution satellite image and the fire perimeter data from GeoMac [91] in the assessment. Another interesting example is the house damage mapping in the 2017 Tubbs Fire in California from New York Times [92]. The reporters employed address point data, fire perimeter data, satellite image data, on-the-ground survey data, and drone data to make a map that provides a complete picture of the effects of this fire. Specifically, they mapped out the locations of the damaged houses and deaths.

In recent years, CAL FIRE has started to use address point data to notify the residents the status of their houses. For example, CAL FIRE leveraged address point data and Web GIS to publish house damage information in the Camp Fire in northern California in 2018. As the most destructive fire in California history, the Camp Fire destroyed about 18,804 structures and killed 86 people [10]. During and after the evacuation process, CAL FIRE used ArcGIS Online as the Web GIS platform to publish house damage data [93]. The damaged houses were divided into several categories based on damage levels: affected (1–9%), minor (10–25%), major (26–50%), and destroyed (> 50%). In addition to house loss data, other data such as a base map and fire perimeter data were also used to implement a map mashup to help the users locate their houses. Moreover, the platform can also take an address or a place name as the input and use geocoding to locate it such that the users could more efficiently locate their houses. Compared with hardcopy maps, Web GIS can provide an interactive user interface and facilitate information dissemination [94].

Note that in terms of communication, the information flow in these existing house damage notification systems is unidirectional. The users can interact with the user interface but cannot directly send information to the public safety officials through these systems. Another downside of using these existing commercial cloud Web GIS platforms is that they are for general use and not for specialized applications such as wildfire evacuation. We still need to design and implement some customized Web GIS platforms for wildfire evacuation purposes. Lastly, users need to pay for these commercial Web GIS platforms, which may make it challenging for under-resourced counties to implement and maintain these systems. In this regard, similar Web GIS platforms based on open source GIS tools that can use address point data for house damage assessment and notification will be of greater value. Additionally, allowing for two-way communication between local authorities and residents through the customized Web GIS platform can facilitate the sharing of real-time information that can improve decisions related to protective actions of both authorities and residents. The past few years have witnessed the rapid growth of open source GIS, and there are open source alternatives for every type of GIS software [95,96]. However, this area is under-researched, and more efforts should be made to develop relevant open source solutions.

## 5. Discussion

The above review and relevant examples have revealed the potential value of address point data in wildfire evacuation applications and the necessity of a national address point database for improving wildfire public safety in the U.S. Recent events highlight the need for more precise national WUI mapping, improved evacuation modeling, support systems that can help aid in the section of evacuation zones, and improved information sharing between evacuees and local officials beginning with the warning and ending with the reentry message. Note that a national address point database can also similarly play a significant role in these wildfire evacuation applications in many other countries such as Australia and Canada. For example, shelter-in-home (stay and defend) is also a popular protective action in Australia [16,18,97], and a national address point database can facilitate household-level protective action warnings in Australia. We provide a further discussion on the use and development of national address point databases in the U.S. below, which can also shed light on relevant research in other countries.

First, developing and maintaining a national address point database in the U.S. is a tremendous endeavor and requires more than merely a technical task. To that end, more research on other potential applications of a national address database necessitates further study. The NAD project organized by DOT involves different levels of government agencies, which poses a challenge to the development and future management of the database. From a technical perspective, it is important to consider how to align the NAD with other types of national spatial datasets such as the national GIS data from the U.S. Census TIGER project. We need to compile spatial data from a variety of sources in many applications. For example, there will be a need to compile relevant road data, administrative zone data, and population data from U.S. Census or local authorities for evacuation decision-making in wildfires or other types of hazards. In the U.S., GIS data management platforms and systems could vary by county. Thus, it will be more convenient and efficient to compile these data from a national database. Lastly, from an application perspective, the developers of the NAD should incorporate more inputs from domain experts such that the NAD can better satisfy their needs in different applications. Similarly, the developers of the OpenAddresses project can also benefit from relevant research on address point data applications and further improve this project. In this article, we list the applications of address point data in wildfire evacuation applications, which can shed light on how to incorporate the needs in other applications into the development of the national address point database. Note that a national address database can also be used in many other applications. For example, it could be potentially used for more accurate geocoding. Geocoding quality has significant impacts on subsequent spatial analysis and decision-making [98]. Address point data have been widely used as the ground truth data to evaluate the spatial accuracy of a geocoding procedure [30]. A national address point database could potentially be used for geocoding directly if it has a good coverage and consistency and an acceptable level of spatial accuracy.

Further research still needs to be conducted to investigate the quality of the existing address point data in the two projects. The two relevant projects towards building a national address database in the U.S. covered in Section 2 are different in the way they are organized and conducted: the OpenAddresses project is an open, crowdsourcing data initiative organized by the open source community, while the NAD project is an initiative coordinated by different U.S. government agencies. Which strategy will be more applicable in developing and maintaining a national address point database in the U.S. in the long run remains to be seen. From a project management perspective, the contributors of the NAD should develop an effective and efficient workflow to coordinate collaboration with other agencies. A more pressing need will be to further examine the data quality of these two projects. Different metrics can be employed to evaluate the data quality, e.g., coverage, accuracy, update interval, consistency, etc. Update interval is a particularly important aspect of address point data for wildfire evacuation applications. As the WUI has expanded, households and neighborhoods have been rapidly added over time. “Missing” households in out-of-date address point databases could result in errors in evacuation warning and zoning, traffic modeling, and house loss notification and assessment. Keeping address point data up-to-date will pose a significant challenge to both the OpenAddresses and the NAD project.

With regard to data management, the two national address database projects mentioned in Section 2 differ in terms of the degree of openness. Although both projects provide open data to the public, the OpenAddresses project employs an open, transparent data format, while the NAD project uses ESRI geodatabase format to distribute the address point data. Thus, the NAD project by default will be restricted within the ESRI ArcGIS ecosystem, which will pose a challenge to those GIS users in open source community. Another huge difference between the two projects is in project management. Specifically, the OpenAddresses project is hosted on an open source platform GitHub, and everyone can participate and contribute to this project. Furthermore, the version control software Git can significantly facilitate project management and improve efficiency. As for the NAD project, although the developers can also use tools such as Git, it is within these government agencies and does not allow people from outside these agencies to participate and contribute. The WUI is expanding rapidly, and new addresses will be created with the development of new neighborhoods. Many applications (e.g., evacuation warning, house loss notification/assessment) in wildfire evacuations require that the address point data used should be the most recent data and a national address point database should be periodically updated. This poses a significant challenge to both the OpenAddresses and the NAD project. More research should be conducted to further investigate the pros and cons of the data management strategies in these two projects and how to make it more efficient.

Lastly, developing a useful national address point data is only the first step towards building an effective cyberinfrastructure for various wildfire evacuation applications. A significant amount of further work still needs to be accomplished before address point data can be effectively used in the above-mentioned applications in wildfire evacuation.

The past few years have witnessed the rapid development in geospatial cyberinfrastructure [99,100]. A geospatial cyberinfrastructure is a combination of data sources, computing platforms, network protocols, and computational services that can be used to perform science or other data-rich applications through geospatial principles [100]. Cloud computing has enabled us to build more scalable computer systems for various applications [99,101]. In the context of wildfire evacuation, we could employ cloud computing to build scalable systems that could be readily deployed and used when needed. This could significantly reduce the cost the state or county governments need to bear. However, it should be noted that even if this is technically feasible, a significant amount of research needs to be conducted on the management side to figure out what systems should be hosted at what level (i.e., federal, state, or county) and how due to the decentralized structure in GIS data management in the U.S.

## 6. Conclusion

We provide a review of the applications of address point data in wildfire evacuation research and summarize the potential values of a national address point database in facilitating wildfire evacuation. Moreover, we also present several real-world examples of address point data applications in current wildfire evacuation practice to further justify the pressing needs for a national address point database. This work shows that a national address point database could be an invaluable asset to wildfire evacuation research and practice. The findings could be leveraged by the developers of the NAD and the OpenAddresses project to improve their national address databases to more effectively support various evacuation applications. This work can also shed light on how to better use address point data in other types of evacuation studies and applications.

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