Fire Safety Journal 143 (2024) 104076

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Integrating dynamic wildland fire position input with a community fire spread simulation: A case study of the 2018 Camp Fire

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ARTICLE INFO

Keywords:
Fire spread simulation
Wildland-urban interface
Continuous fire tracking
Camp Fire
SWUIFT
Community definition

ABSTRACT

Wildland fire simulation models can be used to inform wildfire risk assessment and mitigation strategies. However, existing models tend to simulate fire spread only inside the wildland or the wildland-urban interface (WUI) communities, but not in both. As a result, there is a need to integrate methodologies to enable seamless simulations of events that ignite in the wildland and continue spreading both across the wildland and inside WUI communities. This paper investigates a systematic methodology to provide a WUI fire spread model with the capacity to assimilate dynamic wildland fire position inputs. The paper uses the streamlined wildland-urban interface fire tracing (SWUIFT) model to simulate WUI fire spread, weather radar data to track the fire line inside the wildland, and the 2018 Camp Fire event as a case study. The work proposes and evaluates a methodology based on a 'Three-Domain Solution' (Wildland, Transition, Community) for a smooth fire transition between wildland and community settings. Alternative approaches are examined to describe the boundaries of a Community Domain for simulation purposes. Existing WUI definitions are studied, and considering the analysis results, a non-WUI neighborhood-based housing density (NBHD) method is proposed. This work establishes a systematic approach for a unified wildland-WUI fire simulation.

1. Introduction

Wildfires are natural events with an important role in ecosystem dynamics [1], but they also bear the potential to be destructive, particularly when they reach communities and impact valuable resources. In recent decades, wildfires have significantly increased in frequency and intensity [2,3], with soaring associated socioeconomic costs from the loss of life, health impacts, damaged or destroyed infrastructure, and firefighting activities. This trend has been driven by an increase in human activities within the wildland [4], the expansion of the wildland-urban interface (WUI) [5], and climate change [6]. With none of the driving factors expected to recede in the near future, it becomes crucial to better understand and characterize the behavior of wildfires to facilitate an optimized allocation of already limited resources and provide solution pathways that would enable a future of co-existence with wildfires.

Large wildfires can overwhelm firefighting efforts and overtake other defensible actions, impacting large communities and causing destruction. Consequently, communities built in areas with potential wildfire exposure need to be designed for the hazard, treating wildfires in a similar way to other hazards such as hurricanes, tornadoes, or earthquakes [7]. Nonetheless, there is a need to predict the level of damage that a wildfire event may cause in a community to identify and mitigate vulnerabilities and quantify risk. This need can be addressed with the development of accurate simulation and modeling tools. More specifically, models focused on the fire spread inside WUI communities can provide a projection of the expected number and location of damaged or destroyed structures; however, such models are currently scarce [8–10], and their scope is usually limited to the simulation of fire progression inside communities or vulnerability assessment of structures. On the other hand, several models that focus on the simulation of fire spread through the wildland are available [11–17], but these models typically lack the requisite characteristics of urban fuel and operate at spatial resolutions that are incompatible with the dimensions of individual

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https://doi.org/10.1016/j.firesaf.2023.104076
Received 7 June 2023; Received in revised form 14 November 2023; Accepted 11 December 2023
Available online 13 December 2023
0379-7112/

structures.

Although existing models, whether wildland-focused or WUI-focused, can cover complementary parts of the wildfire problem domain, detailed research on the integration of the two methods is still needed. Community fire spread models require information about the initial ignitions that occur inside or close to the communities as input. This input can be classified as static or dynamic. A static fire position refers to a well-defined spatial and temporal location of the fire that is known when the community simulation is set up, and from which the simulation can take over. In contrast, a dynamic fire position refers to a series of changing fire locations that are partially or completely unknown when the community simulation is set up. That is, a dynamic fire position represents a wildland fire that is progressing over time, as informed by a source external to the community fire spread model (e.g., real-time observations or results from a wildland fire simulation model). Given that a dynamic fire position provides an independent and initially unknown input to a community fire spread model, a set of rules is required to prevent conflictive progression of the fire line across domains and to facilitate the connection between the input and the community fire spread model.

The objective of this paper is to evaluate and advance the capabilities of a WUI-focused fire spread model to receive and assimilate dynamic wildland fire position inputs for a seamless fire simulation from wildland to WUI communities. The streamlined wildland-urban interface fire tracing (SWUIFT) model [8] is used to simulate fire spread inside WUI, weather radar data is used to track the fire line inside the wildland, and the 2018 Camp Fire is selected as the case study. The methodology described in this paper can be adapted to integrate a WUI-focused fire spread model with wildland fire spread models in the future.

1.1. The SWUIFT model

SWUIFT [8] is a semi-empirical model that accounts for thermal radiation and fire spotting mechanisms to simulate fire spread inside an urban environment. The model simplifies a community into a raster and assigns a fuel type (i.e., structure, vegetation, or non-combustible) to each cell based on the predominant landcover. The current version does not differentiate buildings with different features (e.g., roof types, siding material); however, non-combustible structures may be manually identified and separated from the rest of the structures. Initial ignitions, which can occur in vegetation or structure cells, are provided as input by the user. Subsequently, the model estimates fire progression from the burning cells to the rest of the grid based on the input wind velocity and direction at regular timesteps (e.g., 5-min increments). The fire evolution in the structure cells is based on 10 10 3 m burning compartments. After the fire in a burning structure cell develops, it spreads to adjacent cells within the same structure and produces firebrands and thermal radiation. Burning vegetation cells contribute to the fire spread only by firebrand generation, and similarly unburned vegetation cells can only ignite by fire spotting.

SWUIFT simulations have been validated using historical cases of wildfires during which WUI communities were affected [8,18 20]. The validation process used historical wildland fire locations and wind conditions as inputs, and evaluated the accuracy of the simulated fire propagation inside the communities based on documented observations from the actual incidents. In the applied scenarios, the input for the initially known locations of fire was static. This led to the use of spatial simulation domains that tightly encompassed the physical extent of the analyzed communities with relatively small portions of wildland areas in the surroundings, particularly in the direction of the approaching fire. Nonetheless, one of the main objectives of WUI wildfire modeling lies in its use for predictive purposes, where the simulation results can inform risk assessment and decision-making processes. For pre-fire planning and risk assessment, a series of wildfire scenarios need to be considered for which the approaching times and locations of the wildland fire to the WUI community will vary. Therefore, it is preferred for the spatial simulation domain to include larger buffers of wildland vegetation around a community to accommodate the different scenarios and the initially unknown locations through which the fire line could reach a community.

Spatial domains with large portions of continuous wildland vegetation represent a challenge for SWUIFT simulations. The model has been developed and validated for fire progression inside communities, where the landcover is predominantly classified as structures or non-combustible. Although SWUIFT also accounts for the presence of vegetation cells to capture the effects of vegetation around structures, the procedure to simulate fire spread across vegetation is substantially simplified in comparison to wildland fire simulation platforms, which are exclusively developed for fire spread simulation in the wildland. In SWUIFT, vegetation is only considered as such if it has a height larger than 0.30 m (1 ft), and fire spread from and to vegetation cells can only occur due to fire spotting. Despite the simplifications, the model results have shown good accuracy for WUI community simulations [8,18 20], while having a low computational cost.

The current SWUIFT simulation methodology needs to be adjusted to facilitate simulation on large domains where wildfires could actively and independently progress through the wildland, reach communities at initially unknown spatial and temporal locations, and seamlessly transition into the urban area. Since models with reasonable accuracy have been developed for the simulation of fire spread within the wildland, an efficient solution is to enable SWUIFT to assimilate input from such models and provide a framework for coupled feedback between independent simulations. An important step towards a continuous tracking of fire in the wildland and urban areas is to define and connect the associated domains, that is, how and where SWUIFT should take over from a dynamic wildland fire position input. Therefore, a boundary for SWUIFT s analysis domain needs to be defined and the governing rules for how the model will connect with the dynamic input at the boundary should be established. Although the paper uses SWUIFT to establish the relevant domains, the proposed methodology can be adapted for the general integration of wildland and WUI fire spread models. The rest of this paper will focus on defining and implementing the relevant domains for a continuous tracking of fire.

1.2. Outline

This paper is organized as follows: Section 2 describes the case study (2018 Camp Fire). Section 3 presents the sources of information and parameters for the SWUIFT model setup of the Camp Fire that are used in the subsequent sections. Section 4 presents a sensitivity analysis of the SWUIFT simulation in the wildland to various initial locations of a static wildland fire input. Section 5 explores different approaches to define community limits that can serve as the boundary of the SWUIFT analysis domain. A standardized procedure to define a Community Domain for generalized cases is proposed. In section 6, a set of rules for the dynamic integration of wildland fire and SWUIFT domains are defined, and a 'Three-Domain Solution (Wildland, Transition, and Community) is proposed. Section 7 evaluates the performance of the proposed methodology based on the accuracy of the simulation results against the historic and well-documented 2018 Camp Fire event. Sections 8 and 9 provide a summary of findings and conclude the paper.

2. Camp Fire case study

The 2018 Camp Fire in California has been selected as a case study for this research, provided that sufficient data is publicly available, particularly detailed documentation of the fire progression through the wildland [21] and inside the Town of Paradise [22], which was the most affected community during the event. The available data provide inputs for the model and allow for its validation.

According to the Camp Fire Public Report [23], the fire was first spotted approximately at 6:20 a.m. local time on November 8th, 2018, close to Pulga Bridge, about 13.7 km to the northeast of Paradise. Initial assessments of the fire, performed by firefighters around 6:44 a.m. concluded that the wind conditions made it impossible to attack the fire, and the efforts were refocused on evacuating the residents of Pulga, a nearby community. The fire continued to rapidly progress, traveling southwest and reaching the Town of Paradise at 7:44 a.m. The fast rate of fire spread, in addition to the short distance between the ignition location and the surrounding communities, made the suppression efforts difficult with evacuation orders being the best alternative for emergency response management.

The Camp Fire destroyed Paradise, as well as the nearby communities of Magalia and Concow. In total, 85 fatalities were reported, along with 18,804 destroyed and 754 damaged structures, and a total estimated loss of more than $16.6 billion [22]. These numbers placed the Camp Fire as the deadliest, most destructive, and most expensive wildfire in California's history. This incident was also the most expensive natural-related disaster around the world in 2018 [24].

3. Input sources and model setup

The spatial domain for all the SWUIFT simulations performed in this study is a rectangular area of 830 km^2 limited by the geographical coordinates 39.84 (to the North), 39.61 (to the South), −121.41 (to the East), and −121.79 (to the West), as shown in Fig. 1. This domain encompasses the area affected by the Camp Fire on November 8th, 2018. For improved clarity, the simulation results that focus on fire spread inside the community will be presented for the "visualization domain" (shown in Fig. 1), which is a reduced area close to the Town of Paradise.

The characteristics and impacts of the Camp Fire have led to extensive research about the event, leading to detailed documentation that is not typically available for other wildfire incidents. In this study, the fire progression in the wildland is obtained following a recently proposed method to estimate fire perimeters based on weather radar observations [21]. This method provides high-resolution (~250 m and 15 min) fire positioning data. Additionally, information regarding the fire ignition time of specific structures inside Paradise is available from a study by the National Institute of Standards and Technology (NIST) [22]. A compiled version of these observations is shown in Fig. 2. The NIST study is used for assessing the performance of the SWUIFT simulation results in Section 7. The wind direction and speed data are obtained from the Jarbo Gap Remote Automatic Weather Station (RAWS) [25]. Both the wind direction and speed data are constant for the spatial domain, but are updated at every hour (i.e., the data has a 1-h temporal resolution).

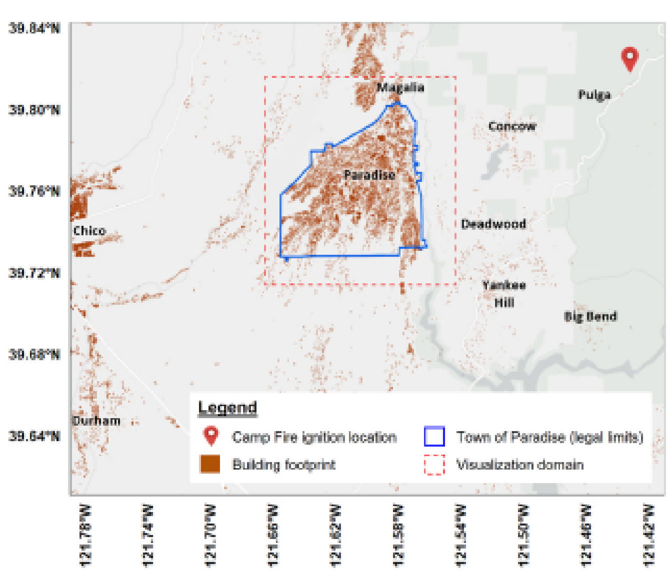

Fig. 1. Spatial domain for analysis of the Camp Fire.

Finally, the land cover input is prepared by combining the information from the Microsoft US Building Footprints [26] and LANDFIRE's 13 Anderson Fire Behavior Fuel Model (version us_140) [27].

In all the cases, the land cover information is represented on a grid of 13.88 m square cells. To create this grid, LANDFIRE's original raster is up sampled from a 30 m to a 13.88 m resolution by disaggregation. A binary raster is then created by classifying all cells with categories where the fuel bed depth [28] is equal to or greater than 0.30 m (1 ft) as vegetation, and all others as non-combustible. The building footprints are rasterized and intersected with the binary raster, with buildings having priority over the binary raster's categories. The simulations run at 5-min timesteps with all parameters and assumptions following the standard SWUIFT model [8]. Table 1 summarizes the variations between the simulated cases that will be discussed in this study.

4. Sensitivity analysis: SWUIFT simulations in the wildland with different static wildland fire input locations

Providing SWUIFT with a capacity to assimilate dynamic wildfire position input requires an understanding of the performance of SWUIFT in the wildland. The aim is to identify regions with respect to the analyzed community at which SWUIFT may take over fire spread predictions from a known wildland fire position. It can be logically inferred that SWUIFT results are less accurate in the wildland than in community settings due to its simplified approach for treating vegetative fuel. Nonetheless, until now no analysis has been carried out to corroborate this inference and to identify the ideal location of the initial fire position input with respect to the community limits. Therefore, this section presents a sensitivity analysis to study the effects of various initial locations of static wildland fire on the simulation results in the wildland.

The weather radar-derived fire perimeters provide fire location data every 15 min, starting at 6:30 a.m. local time [21]. It is known that the fire reached the Town of Paradise around 7:44 a.m.; therefore, the sensitivity analysis is performed using the following six fire positions as the input for the SWUIFT simulations: 6:30 a.m. (Case A), 6:45 a.m. (Case B), 7:00 a.m. (Case C), 7:15 a.m. (Case D), 7:30 a.m. (Case E), and 7:45 a.m. (Case F). In all cases, the fire position will serve as an input only for the first timestep of the simulation, implying that subsequent fire progression will be completed by SWUIFT and will not be updated using additional observations. The starting time of each simulation (i.e., timestep 1) is the time of its corresponding static fire position input. The results from the analyzed scenarios up to the point where the fire enters the community are shown in Fig. 3. For all the cases, the wildland fire positions at the initial (left) and final (right) timesteps are displayed.

The results from Fig. 3 show delayed arrivals of the fire front to Paradise, particularly for cases A, B, and C, where the initial fire location was further away from the community. This visual analysis of the results suggests that SWUIFT simulations that start from locations far from a community may result in inaccurate temporal and spatial predictions of the approaching fire front to the community. Nonetheless, to quantify the performance of the simulations, the predicted wildland fire rate of spread (ROS) for each simulation case is compared with the ROS that would have been expected for the fire to reach Paradise at 7:44 a.m. A summary of the expected and predicted wildland ROS is presented in Table 2. In all cases, the ROS is calculated based on the trajectory described by the shortest straight-line distance between the initial fire perimeter and the limits of Paradise. An average error of −36.6% was observed for the predicted ROS.

The ROS error in the wildland appears to be independent of the distance between the initial fire front location and the community. However, an inaccurate fire line carried over for longer distances will result in accumulated inaccuracies in the estimated time of fire arrival at the community. Therefore, the closer the initial distance between the fire and the community, the less error is carried over into the simulation of fire inside the community. For example, the simulation in Case A (with input at 6:30 a.m.), where the fire front was initially located 8.5

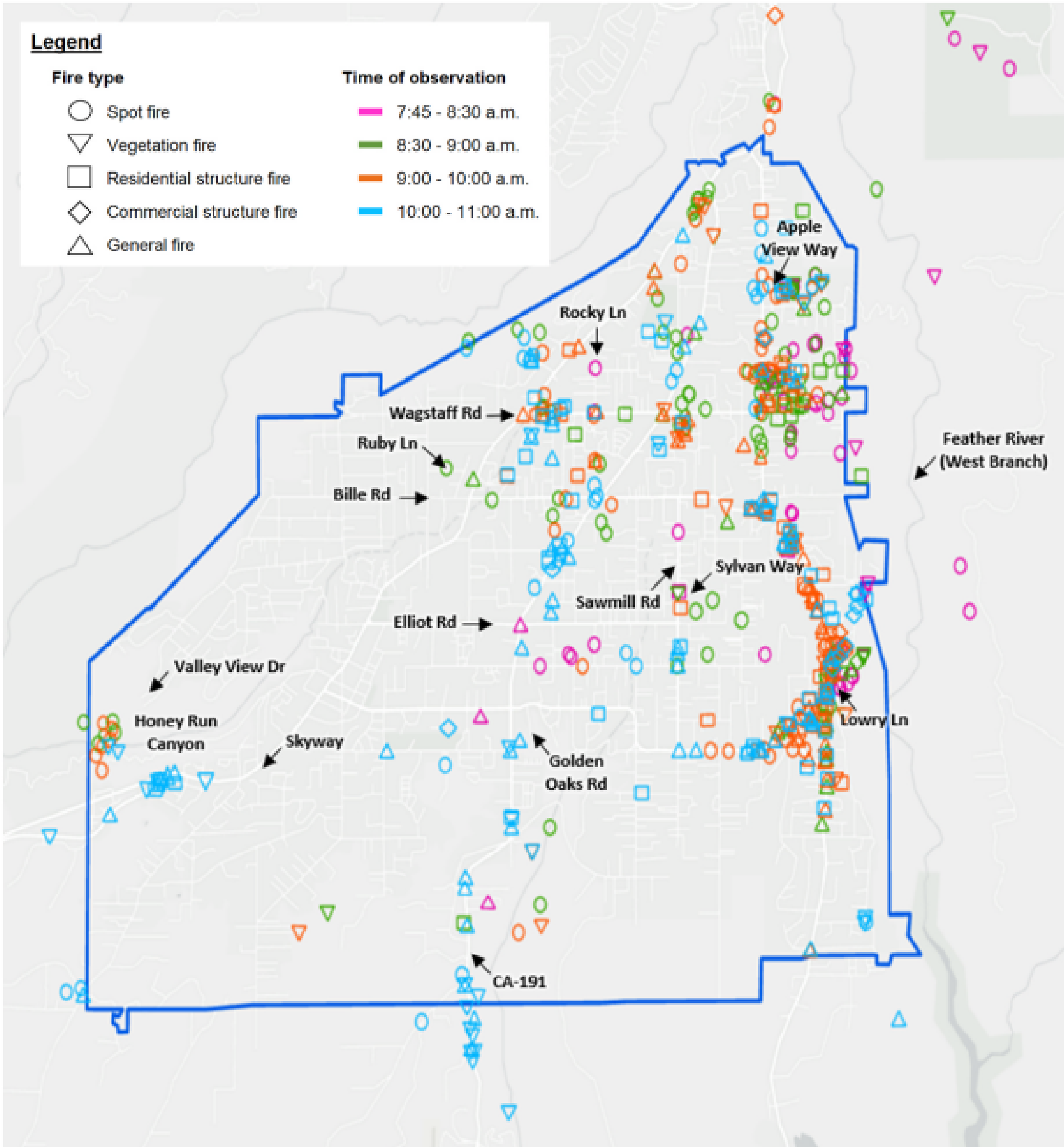

Fig. 2. Fire observations in Paradise during the 2018 Camp Fire adapted from Maranghides et al. [22].

km away from Paradise, resulted in a 41-min delay with respect to the actual event observations. In comparison, the simulation in Case E (with input at 7:30 a.m.), where the fire front was initially located 1.1 km away from the community, indicated only a 6-min delay with respect to the actual time. The observed imprecisions are likely derived from SWUIFT's simplified analysis for vegetation fire, which does not consider variabilities in the vegetation properties and conditions. In addition, the low-resolution wind data that was available and used as an input may have introduced inaccuracies in the simulations. Finally, it is also important to consider that long-range spotting was a key driver of the fire ROS during the Camp Fire event [21]. While SWUIFT incorporates a transport model for firebrands, it is expected to underestimate the long-range spotting contribution.

Another observation that can be drawn from the analyzed cases is that SWUIFT is not capturing well the fire expansion in the across-wind direction through the wildland. Particularly in cases A, B and D, the width of the fire front when arriving to Paradise is smaller than that in Case F, where the fire position comes directly from a weather radar observation. This behavior is expected for uniform wind conditions, similar to the ones used for simulations of Fig. 3. The reason lies in the procedure that SWUIFT follows for transporting firebrands, which is based on the probabilistic approach proposed by Himoto and Tanaka [29]. Under this procedure, the landing distribution of firebrands in the across-wind direction is described by a normal distribution with a small standard deviation. Given that the RAWS wind input used for these simulations has low temporal and spatial resolutions (one average wind speed and maximum gust for the full spatial domain at every hour), the observed behavior of the simulated fire progression within the wildland is expected. Under more realistic conditions, which can be implemented in future studies where high-resolution wind input is available, the fire can be expected to have a greater across-wind expansion due to fire-induced atmospheric circulations, turbulent eddies, and better representation of wind speed and direction.

Overall, the results of the sensitivity analysis confirm that if SWUIFT

Table 1
Description of simulated cases in the paper.

Section	Analysis	Domain of evaluation	Case	Type of wildland fire position input	Simulation starting time	Simulation finishing time
4	WSA	Wildland	Case A	Static at 6:30 a.m.	6:30 a.m.	11:00 a.m.
4	WSA	Wildland	Case B	Static at 6:45 a.m.	6:45 a.m.	11:00 a.m.
4	WSA	Wildland	Case C	Static at 7:00 a.m.	7:00 a.m.	11:00 a.m.
4	WSA	Wildland	Case D	Static at 7:15 a.m.	7:15 a.m.	11:00 a.m.
4	WSA	Wildland	Case E	Static at 7:30 a.m.	7:30 a.m.	11:00 a.m.
4	WSA	Wildland	Case F	Static at 7:45 a.m.	7:45 a.m.	11:00 a.m.
7	TDS	Community	USFS' WUI method	Dynamic	6:30 a.m.	11:00 a.m.
7	TDS	Community	FRAP's WUI method	Dynamic	6:30 a.m.	11:00 a.m.
7	TDS	Community	NBHD method	Dynamic	6:30 a.m.	11:00 a.m.

Note: WSA = Wildland sensitivity analysis; TDS = Three-Domain Solution.

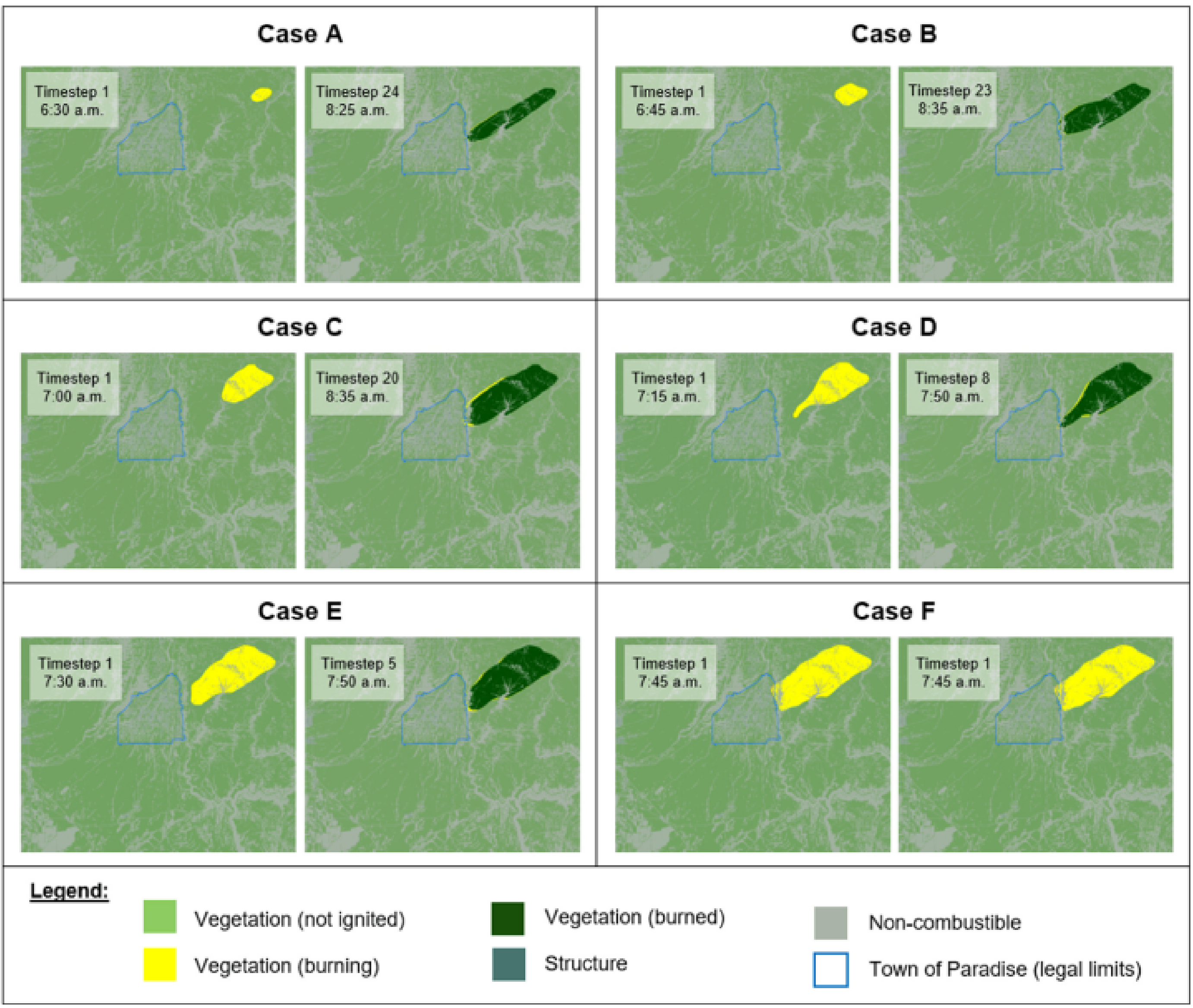

Fig. 3. Results of the six considered scenarios. For all cases, the left panel shows the initial fire perimeter used as a static simulation input, and the right panel shows the fire position at the timestep at which the fire enters Paradise based on SWUIFT simulation.

Table 2
ROS error for the sensitivity analysis cases.

Simulation case	Time of the static wildland fire input	Initial distance from community (km)	Expected wildland ROS (km/h)	SWUIFT s predicted wildland ROS (km/h)	ROS error (%)
A	6:30 a.m.	8.5	6.9	4.4	36%
B	6:45 a.m.	7.7	7.8	4.2	46%
C	7:00 a.m.	5.2	7.1	3.3	54%
D	7:15 a.m.	2.2	4.6	3.8	17%
E	7:30 a.m.	1.1	4.7	3.3	30%
F	7:45 a.m.	0	N/A	N/A	N/A

receives wildland fire inputs that are distanced from the community, errors can be expected in the prediction of fire spread in the surrounding wildland before reaching the community. Therefore, to enable SWUIFT to assimilate dynamic wildland fire input, real-time observations or a wildland fire simulation model (e.g., WRF-Fire) can be used to capture fire spread within the wildland, before transmitting fire boundaries to SWUIFT close to the community. To achieve this, the current spatial simulation domain needs to be classified into independent domains: the Community Domain and the Wildland Domain. The next section will focus on the definition of boundaries between both domains in a consistent manner that can be replicated in future studies.

5. Defining the Community Domain boundaries

An ideal SWUIFT Community Domain is expected to be an area that encloses all the structures connected as part of one or multiple clusters in the community, with an exterior contour that closely follows the boundary line of structures while leaving out any vegetation area that directly connects with the surrounding wildland. Additionally, the mapping procedure for the domain is expected to be (1) as simple as possible to reduce the computational costs and efforts, and (2) generalized enough that it can be applied in different geographical locations. In search of a method that meets these requirements, this section explores different approaches to define and map a Community Domain for SWUIFT predictive simulation purposes.

5.1. Existing definitions

5.1.1. Legal community limits

For the case analyzed in this study, the ‘community of Paradise is legally classified as a town with already defined limits [30]. The legal definitions of boundaries for villages, towns, or cities are usually open to the interpretation of local authorities, who follow criteria that do not necessarily focus on capturing the actual distribution of buildings. As a result, legally defined community limits may not enclose all the structures that appear to be connected to the main cluster of structures, or on the contrary, may include large areas of undeveloped land. Revisiting Fig. 1 to analyze the legal limits of Paradise helps better illustrate this concept. In some locations, the limits appear to follow well the apparent border of the cluster of structures, such as on the east part of Paradise, where the West Branch Feather River basin leads to an abrupt change in the density of buildings. On the other hand, there are locations where the limits of the town appear to go through the cluster of structures without an evident change in the density of structures, such as the north of Paradise, where some of the buildings east of Little Butte Creek are legally part of Magalia. On the south, several buildings are left out of the town limits, while relatively large areas of undeveloped land are left inside. Given that the criteria to define legal limits may not be uniform from one community to another, and may result in the inclusion of wildland areas, alternative approaches are needed to define community boundaries.

5.1.2. WUI community mapping

According to the Federal Register, the WUI is the zone where humans and their development meet or intermix with wildland fuel [31]. The two main categories of communities covered by this definition are ‘interface communities (where a clear boundary between structures and the wildland exists), and ‘intermix communities (where structures intermingle with the wildland). The objective behind SWUIFT is the simulation of wildfire events that affect interface or intermix communities, treating communities as a variety of clustered human settlements where structures and other human-purposed developments are located. This is an intentionally broad definition that may include settlements, villages, towns, or cities.

Mapping WUI areas is important for distinguishing between the homes that are located within the WUI from those that are not, since such maps can affect decisions regarding wildfire risk assessment and mitigation [32,33]. For this reason, different methods have been proposed in the literature to systematically define the location of the WUI based on criteria that use specific vegetation cover and structure density thresholds. In 2009, a study by Stewart et al. [32] analyzed two of such WUI mapping methods and concluded that the differences in the corresponding maps illustrated the complexity of the WUI. The same study concluded that the purpose that inspired the development of each of the methods needed to be evaluated to identify the most convenient map to be used for a specific application. Similarly, a study by Platt [33] investigated various WUI mapping methods by applying them to four different counties in the United States and assessing the resulting WUI areas. The analyzed methodologies varied in the way in which they defined and employed the concepts of structure density, wildland vegetation, and buffer distances around the structures. Platt s study identified how several factors can influence the differences between the generated maps but concluded that all the methods were appropriate for mapping the WUI once their specific tradeoffs were considered. Finally, a more recent description of modern WUI definitions is included in the study of Kumar et al., which focuses on understanding the relationship between the location where wildfires take place relative to the WUI [34].

5.2. Approaches to define Community Domain boundaries

Although the procedure for selecting a Community Domain for a SWUIFT simulation is likely to be informed by an existing WUI map, the concept of a Community Domain for simulation purposes does not necessarily need to match an existing WUI mapping method. In other words, the existence of a Community Domain boundary does not imply that all the enclosed area is officially classified as WUI and vice versa. A Community Domain boundary indicates that any area left outside of the boundary is found to have a vegetation cover for which simulation of fire spread is expected to be more accurate if obtained from a source other than SWUIFT. Since publicly accessible maps based on existing WUI definitions are available, two such definitions are included among the approaches to be analyzed in this study. A third non-WUI definition is proposed, for which the simulation results are compared with those obtained from the existing WUI definitions. Overall, the following three approaches are investigated: (1) the USFS s WUI definition [35], (2) the FRAP s WUI definition [36], and (3) an original non-WUI definition using neighborhood-based housing density.

5.2.1. Approach 1: USFS WUI definition

The first approach to be analyzed is based on the existing WUI maps from the United States Forest Service (USFS) [35]. These maps are publicly available as shapefiles that can be downloaded from the United States Department of Agriculture (USDA) website [37]. For this study, the first version of the geospatial data was obtained and analyzed using geographic information system (GIS) software. The USFS maps the WUI using a methodology that operates at a census block level, classifying each block into different WUI and non-WUI categories. Specifically, any block that has a housing density over 1 structure per 40 acres (6.2 structures per km^2) and a vegetation cover above 50% is classified as 'Intermix WUI'. If the block meets the housing density criteria but has a vegetation cover below 50%, it can be classified as 'Interface WUI' if it is located less than 2.4 km away from a vegetation area (i.e., an area larger than 5 km^2 with a vegetation cover of at least 75%). Otherwise, the block is classified as non-WUI.

A map displaying the USFS WUI cover for the spatial domain of this study is presented in Fig. 4. A contour with the legal limits of Paradise is included as a reference. The USFS's WUI area does not follow well the contour of the cluster of buildings within Paradise if low density interface (light pink shading) and low density intermix (light yellow shading) are included. The resulting area is a better fit when the low density WUI (interface and intermix) is omitted. Although the area obtained from this approach visually resembles the legal limits of Paradise, it offers a uniform procedure that can consistently be followed for different cases.

5.2.2. *Approach 2: FRAP WUI definition*

The second approach considered in this study is based on the WUI maps from The California Department of Forestry and Fire Protection's (CAL FIRE) Fire and Resource Assessment Program (FRAP) [36]. There are several key differences between this mapping methodology and the one used by the USFS. For example, FRAP applies a minimum housing density threshold of 1 structure per 20 acres (12.4 structures per km^2), and areas should be within moderate, high, or very high Fire Hazard Severity zones to be considered as WUI. Additionally, FRAP operates at a consistent resolution (30 m cells) and establishes minimum thresholds for the size of grouped cells. As a result, FRAP's definition results in a smaller WUI area than USFS's definition.

FRAP's WUI maps classify the land cover into four categories: interface, intermix, influence zone, and not WUI. The distinction between interface and intermix is based on the wildland vegetation cover, while the influence zone is assigned to wildland vegetation within a 1.5-mile (2.4 km) buffer from the interface or intermix. The shapefiles with FRAP's WUI are available to the public on CAL FIRE's website [36]; this study works with version 12_3 of the geospatial data. A map displaying the FRAP WUI cover for the spatial domain of this study is presented in Fig. 5. A contour with the legal limits of Paradise and the community building's footprints is included as a reference.

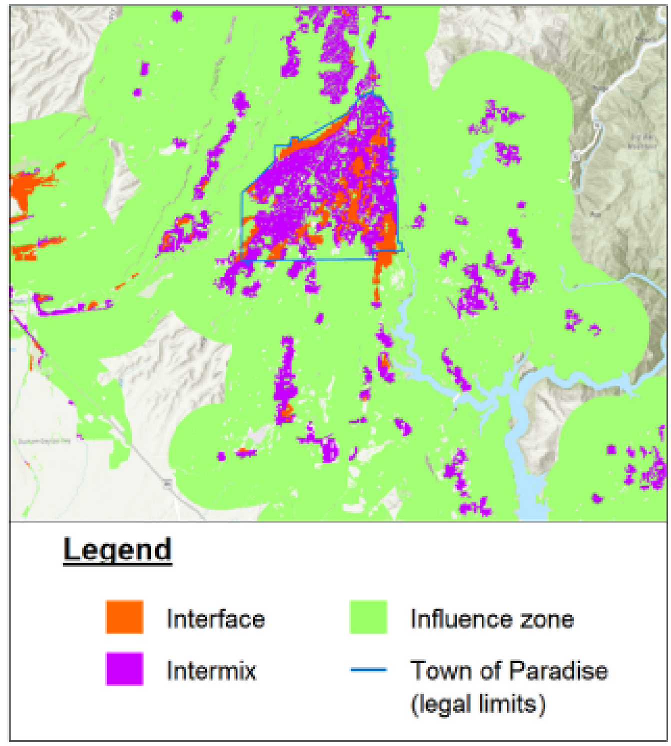

Fig. 5. FRAP's WUI cover for the analyzed spatial domain.

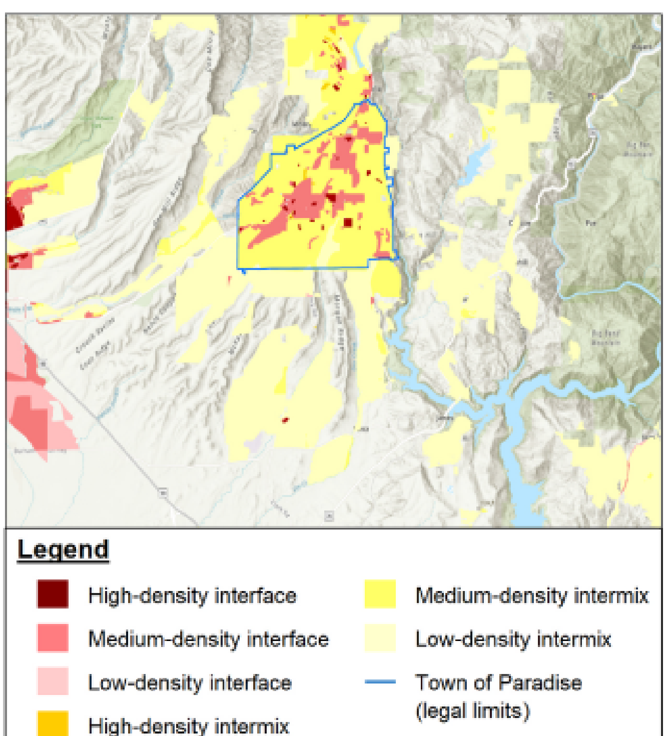

Fig. 4. WUI cover for the analyzed spatial domain based on the USFS definition.

The area described by the combination of FRAP's interface and intermix follows well the contour of the groups of buildings located inside the domain of this study. However, there are many small and scattered independent WUI areas (orange and purple shadings) as well as several empty spaces inside the most prominent WUI clusters that generate 'noise' across the map. Thus, this WUI definition would probably not produce consistent community simulation domains without additional processing. For example, the issues can be addressed by incrementing the minimum threshold for the size of grouped cells, and 'filling' all the empty areas that are surrounded by WUI. The effect of these modifications will be explored in the next section.

5.2.3. *Approach 3: a new non-WUI definition using a neighborhood-based housing density method*

The third approach to describe SWUIFT's Community Domains is a neighborhood-based housing density method, which will be referred to as NBHD. This method follows a procedure that describes community boundaries exclusively based on a contour generated from a minimum housing density threshold. NBHD is not a WUI mapping method since it does not consider vegetation cover or other traditional criteria from WUI definitions. Instead, NBHD focuses exclusively on the generation of homogeneous contours to be used as community boundaries for WUI fire simulations where a connection with a dynamic wildland fire position input is required. The only input for this method is the location of structures, which can be simplified as points. This gives NBHD an advantage in terms of computational efficiency and the potential to be applied in any location around the world.

For this study, the location of buildings is obtained from the Microsoft footprints database [26] (Fig. 6a). Each building is then represented as a point at its geometric center (Fig. 6b). A grid of square bins is defined, and density values are assigned to each bin based on the number of points (structures) inside a square-shaped neighborhood that

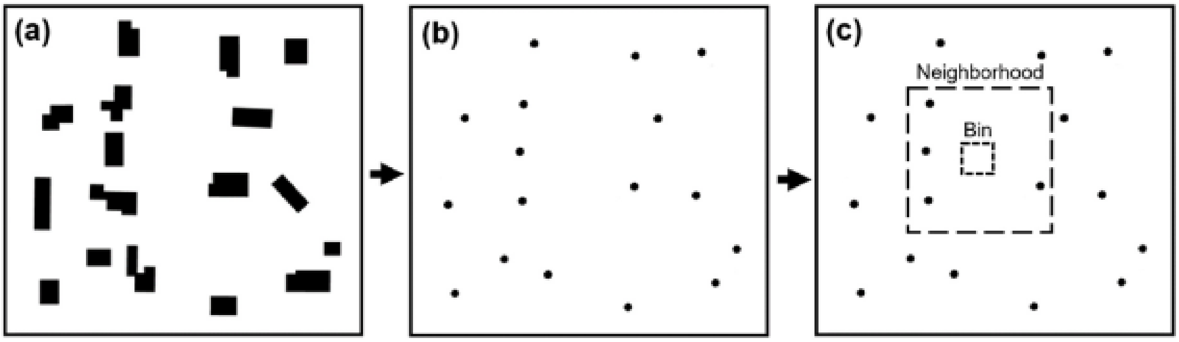

Fig. 6. Steps to complete the NBHD method: (a) retrieve building's footprints, (b) represent each building as a point located in its geometric center, and (c) assign to each bin the density of its square-shaped neighborhood.

is placed around the bin (Fig. 6c). This procedure can be performed using the 'Calculate Density' tool [38] in ArcGIS Pro 3.0.

A set of nine density maps is generated for the analysis domain to investigate the effect of different neighborhood sizes on the generated boundaries. Each density map uses a different neighborhood size to calculate the density of each bin, and areas that surpass specific density thresholds are included in the Community Domain. For all cases, a 50 m bin size is used for the output resolution. The results are presented in Fig. 7.

As expected, the neighborhood's size used to calculate the density for each case affects the shape of the Community Domain. Large neighborhoods tend to assign very similar density values to bins that are close to each other, producing highly homogeneous areas with contours that do not follow the distribution of buildings well. On the other hand, small neighborhoods tend to capture local characteristics, producing noisy areas that tightly follow the distribution of buildings. In summary, there

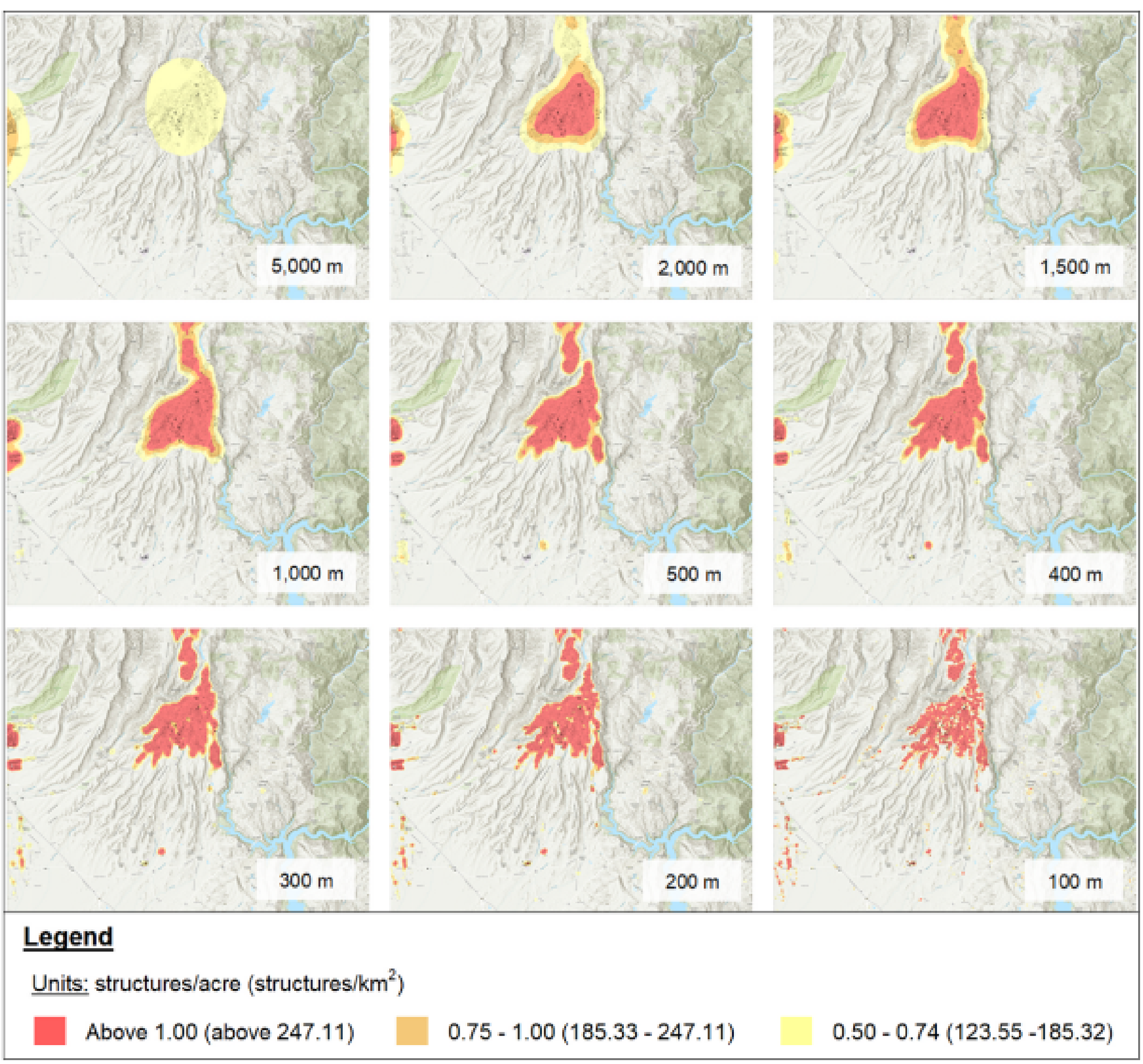

Fig. 7. Housing density maps generated using the NBHD method with different neighborhood sizes, as indicated in the bottom right of each figure.

is a tradeoff between the homogeneity and the precision of the generated areas when setting the size of the neighborhood, and the objective here is to find an optimum neighborhood size considering both attributes.

For the spatial domain analyzed in this study, a neighborhood size of 500 m (250,000 m^2) with a minimum density threshold of 0.5 structures per acre (123.6 structures per km^2) (Fig. 7) produces the best results by generating homogeneous areas that closely follow the external contours from the clusters of structures. Fig. 8 offers a more detailed visualization of this map for the area close to Paradise. The areas produced by this specific combination of parameters will represent the NBHD method in the analysis presented in Section 7.

Having described the three different approaches, the next section will compare simulation results to identify which approach offers the most appropriate solution for SWUIFT to receive input from a dynamic wildland fire position input. As discussed earlier, SWUIFT cannot properly simulate fire spread outside of the Community Domain; therefore, the wildland fire position input will be updated at different timesteps using the available radar-derived fire perimeters. Rules will be established to enable the integration of dynamic fire position input with SWUIFT.

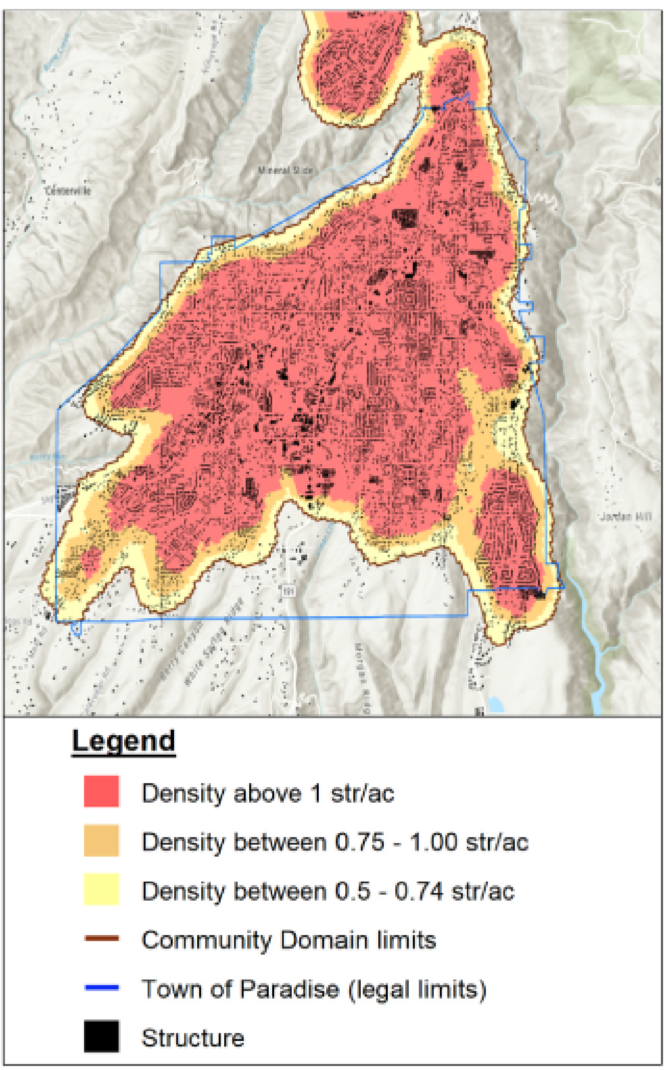

Fig. 8. Visualization of the housing density map generated using the NBHD method with a neighborhood size of 500 m (250,000 m^2) and a minimum density threshold of 0.5 structures per acre (123.6 structures per km^2) for the Town of Paradise.

6. Connecting a dynamic wildland fire position input to the Community Domain

As demonstrated earlier, higher accuracy in SWUIFT's simulation results is expected when the wildland fire position input is close to the community's boundaries. Thus, the need for two different domains becomes evident: a Wildland Domain where the fire progression is dictated by a wildland fire simulation platform or observations, and a Community Domain where the fire progression is dictated by SWUIFT. To prevent conflicting outputs, these domains must be exclusive (no overlap), and only one of the simulation tools must dictate how the fire spreads within a specific domain.

If the Wildland and Community Domains are exclusive, a systematic approach to transfer the wildland fire progression inside the Community Domain must be established. A direct transition of the fire line at the boundary oversimplifies the problem because such a solution would not account for the occurrence of ignitions inside the community caused by firebrands generated from wildland vegetation away from the community boundaries. This is important, since fire spotting is considered a major mechanism of fire spread during wind-driven wildfires [39–41], and firebrands can pose an ignition risk for vegetation and structures located several kilometers away from their point of origin [42]. SWUIFT can simulate the generation, transportation, and landing of firebrands for both structure and vegetation cells, and therefore, it is possible and convenient to allow SWUIFT to generate and transport firebrands even before the fire has reached the boundary between the Wildland and Community Domains. Such an approach is beneficial when wildland fire input comes from observations of an actual fire or the results of an existing wildland fire simulation model that cannot simulate fire spotting. It is known that the distance traveled by a firebrand depends on the wind speed [43] and that their along-wind landing can be modeled by a lognormal distribution [29]. This implies that the probability of spotting decreases with distance from the source. Therefore, a computationally efficient procedure can be implemented by limiting the firebrand generation area to a certain distance around the Community Domain considering how far the firebrands can reach. Thus, a third Transition Domain is introduced between the Wildland and the Community Domains.

Inside this Transition Domain, the source of fire progression in the wildland (observations or a simulation tool) should remain in charge of the fire spread inside the domain since the source of wildland fire spread is expected to provide more accurate fire spread input. At the same time, SWUIFT can be partially activated to simulate only the generation and transport of firebrands across the region. These firebrands will only have the capacity to cause new ignitions if they land inside the Community Domain or over a structure pixel (regardless of where it is located). If firebrands land over a vegetation pixel outside the Community Domain, no ignition will occur since this can result in conflicting fire propagation within the wildland.

The Transition Domain can be represented as a buffer that surrounds the Community Domain, containing vegetation cells that are located close enough to the community to be considered as a possible source of firebrands with the capacity to reach community pixels and cause ignition. In SWUIFT, the transfer mechanism for firebrands adopts the probabilistic distributions proposed by Himoto and Tanaka [29]. Eq. (1) specifies the probability of a firebrand to travel distance x, where $\sigma_x = 0.3$, $\mu_y = 0$, $\sigma_y = 4.85$, and $\mu_x = \ln(30 \times v)$, and v is the wind speed in m/s.

$$p(x) = \frac{exp\left\{-\frac{[\ln(x)-\mu_x]^2}{2\sigma_x^2}\right\}}{x\sigma_x\sqrt{2\pi}} \quad (0 < x < \infty) \qquad \text{Eq. 1}$$

For this study, the maximum wind speed within the input data (17.9 m/s) was used to determine the distance from which no more than 1% of the generated firebrands are expected to reach the Community Domain during a SWUIFT simulation, even with the most favorable wind direction. It was found that a Transition Domain described by a 1080 m buffer around the Community Domain sufficiently meets this requirement. This approach to characterize the Transition Domain is convenient, since it is directly related to how SWUIFT operates, and can be adjusted as a function of the wind conditions for future cases of study.

In summary, a 'Three-Domain Solution' is proposed to define regions with different rules within the spatial domain where SWUIFT receives dynamic wildland fire position input. SWUIFT is inactive inside the Wildland Domain, and the fire spreads as indicated by a wildland fire simulation platform or observations. Inside the Transition Domain, SWUIFT becomes partially activated and simulates the generation and transportation of firebrands. These firebrands can ignite any combustible pixel inside the community, as well as structure pixels in any other location. Finally, inside the Community Domain, SWUIFT is completely active and simulates the fire spread. The concept of the Three-Domain Solution is illustrated in Fig. 9.

7. Comparison of the proposed approaches to determine the Community Domain

This section completes the assessment of the proposed approaches for the definition of the Community Domain, considering a dynamic wildland fire position input and the Three-Domain Solution concept described in the previous section. Therefore, the following Community Domain options are selected as simulation inputs: USFS WUI, FRAP WUI, and the NBHD method. The resulting Community Domains for the case study are displayed in Fig. 10. The minimum area threshold used to obtain an independent Community Domain area is 1 km^2. As mentioned earlier, any overlooked area that is surrounded by the Community Domain is added to the domain.

All the simulation cases are run following input sources and model setup discussed in Section 3, with the exception that the Three-Domain Solution is adopted. Therefore, SWUIFT operation is completely or partially limited in the Wildland and Transition Domains, respectively. Any fire spread outside of the Community Domain is based on the weather radar data. Fig. 11 provides the simulation results for the USFS

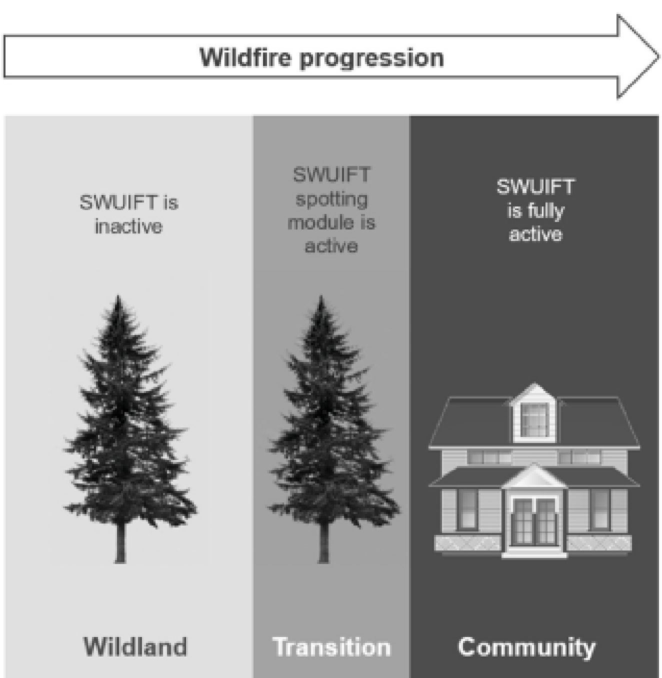

Fig. 9. Three-Domain Solution concept for integrating dynamic wildland fire input and fire spread modeling in a community.

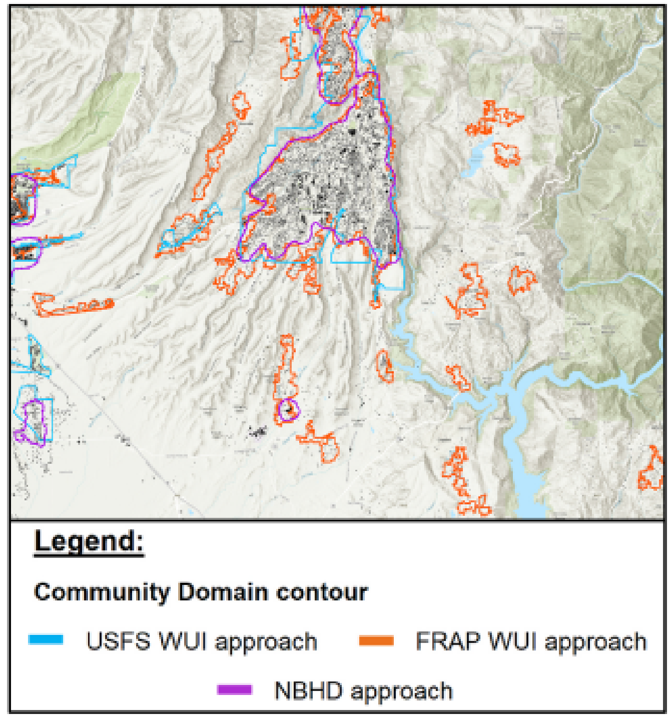

Fig. 10. Community Domains obtained from the USFS WUI, FRAP WUI, and NBHD approaches.

WUI, FRAP WUI, and the NBHD methods. In all the cases, a 1080 m buffer around the Community Domain is used as the Transition Domain.

A visual inspection of the simulation results (Fig. 11) shows low variability in the predicted fire spread inside Paradise among the different Community Domain definitions. By 8:30 a.m., the results from the three cases indicate that the fire has started spreading inside Paradise from the north-east. The fire is predicted to have reached the vicinity of Rocky Ln, matching NIST's observations (Fig. 2, magenta symbols). To the south, the simulations indicate that the fire has crossed Elliot Rd, but the observations show that the fire is further west by about 1.2 km. By 9:00 a.m., the results predict the fire reaching the area of Ruby Ln between Bille Rd and Wagstaff Rd, matching the NIST observations (Fig. 2, green symbols). In the south, the west progression of the fire is now in agreement with the observations, although it is 0.8 km away from the observations near CA-191. By 10:00 a.m., the fire is predicted to have crossed the Skyway and CA-191. In the north, the predicted fire front is 0.6 km away from the cluster of observations (Fig. 2, orange symbols) made at the Honey Run Canyon, south of Valley View Dr. To the south, the predicted fire front reaches the observations made to the west of CA-191. Finally, by 11:00 a.m., all the simulations predict that the fire has impacted most of Paradise, which agrees with the NIST observations for the respective time (Fig. 2, cyan symbols). Based on this qualitative analysis, the simulation results for the three evaluated cases are found to be relatively accurate; however, a quantitative assessment is carried out to confirm this observation.

To complete a quantitative assessment of the results, polygons that represent ignited areas at different times are generated from the fire observations by NIST (Fig. 2) and compared with SWUIFT results from the three approaches. This procedure is performed using the 'Aggregate Points' tool [44] in ArcGIS Pro 3.0. To account for the low density of available observations, the polygons are generated using an aggregation distance (i.e., the maximum distance between points that are clustered) of 2 km. All the fire observations before each evaluation time are used to generate the respective ignited area. Also, the ignited areas are limited to the boundaries of each community domain. Fig. 12 shows the ignited areas generated from NIST's fire observations, as well as those obtained

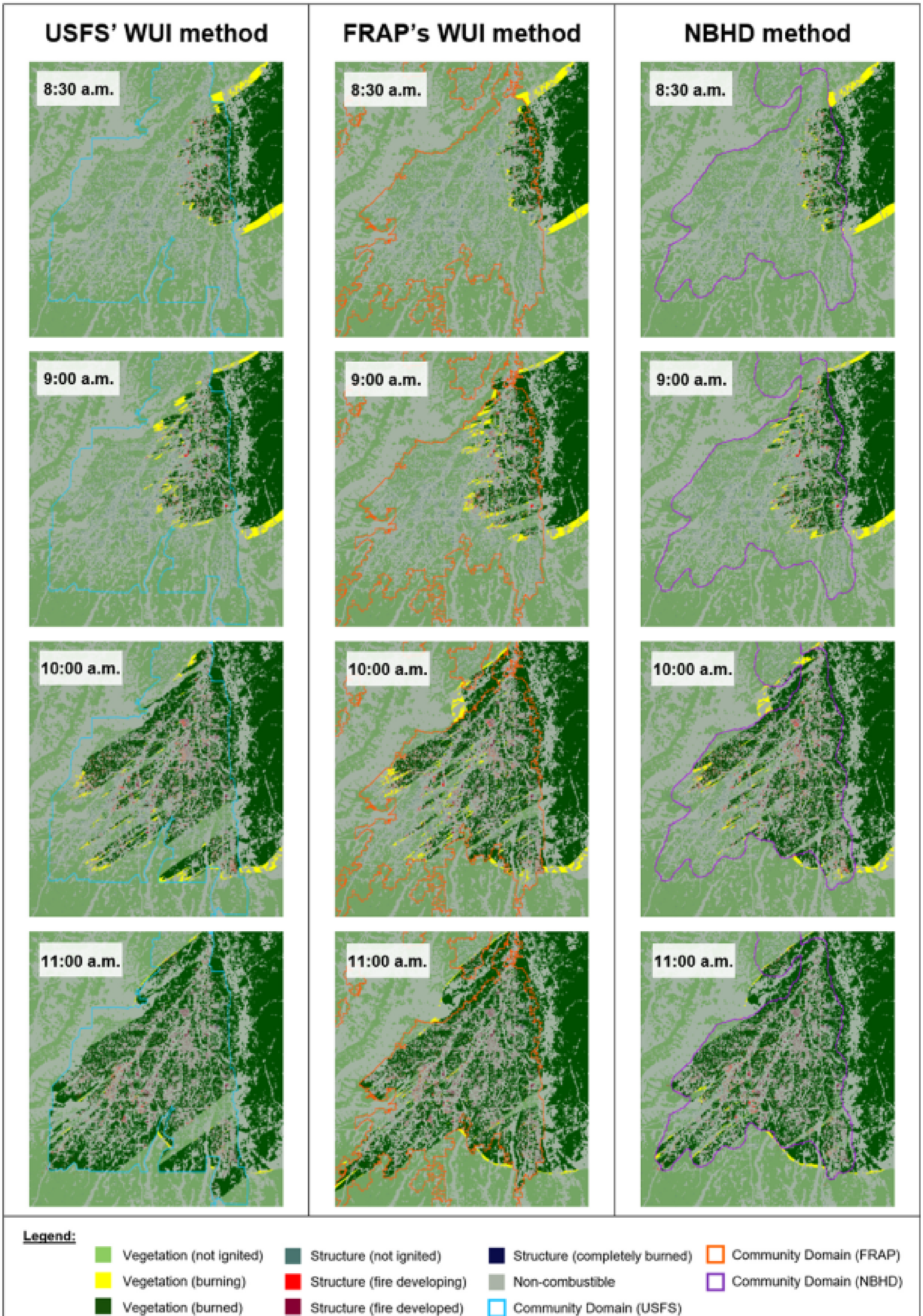

Fig. 11. SWUIFT simulation results using the Three-Domain Solution and Community Domains defined by the USFS's WUI, FRAP's WUI, and NBHD methods.

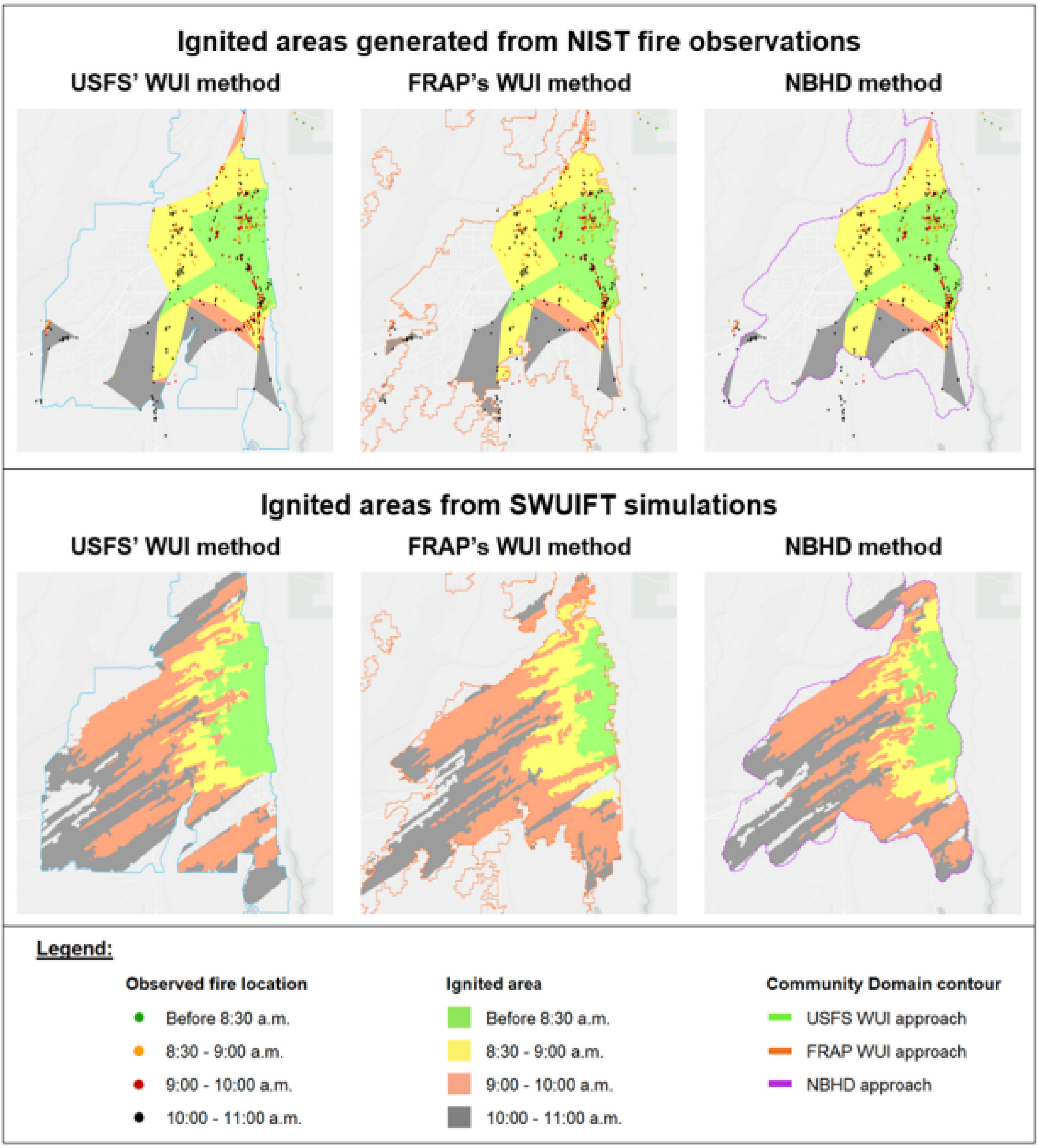

Fig. 12. Ignited areas inside the Community Domain according to fire observations and simulation results.

from SWUIFT simulations. The points from NIST observations are included in the maps for reference. The area and centroid coordinates for all the ignited areas are presented in Table 3.

The similarity between observed and simulated ignited areas is evaluated using three metrics: (1) distance between centroids, (2) Jaccard Index [45] (Eq. (2)), and (3) Sørensen–Dice Index [46,47] (Eq. (3)). For both indexes, A is the ignited area generated from the NIST fire observations, and B is the ignited area generated from SWUIFT observations. Both indexes range from 0 to 1, with a value of 0 indicating total dissimilarity, and a value of 1 indicating total similarity. The metrics for all the cases are reported in Table 4.

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|} \qquad \text{Eq. 2}$$

$$SDI(A,B) = \frac{2|A \cap B|}{|A| + |B|} \qquad \text{Eq. 3}$$

The quantitative assessment also shows low variability in the predicted fire spread inside Paradise among the different Community Domain definitions. The metrics indicate a moderate similarity between the predicted and observed ignited areas. It should be noted that the generated polygons from fire observations may underestimate the extent of fire considering that NIST data do not cover all ignitions. The results validate the use of a Community Domain to limit the area where SWUIFT will be active during predictive simulations and the Three-Domain Solution.

Overall, no clear advantage that justifies the use of one of the approaches over the rest can be observed. Nonetheless, there are other important factors to take into consideration: the availability of inputs and the computational cost. In terms of inputs, the two approaches

Table 3
Areas and centroid coordinates for observed and simulated ignited areas.

Case	Time	Ignited areas generated from NIST fire observations			Ignited areas generated from SWUIFT simulations		
		Area (km^2)	Centroid s coordinates		Area (km^2)	Centroid s coordinates	
			X	Y		X	Y
USFS	8:30 a.m.	7.60	121.5825	39.7710	6.42	121.5781	39.7738
	9:00 a.m.	17.59	121.5898	39.7704	12.00	121.5841	39.7739
	10:00 a.m.	18.91	121.5895	39.7696	29.36	121.5965	39.7657
	11:00 a.m.	24.78	121.5946	39.7627	44.70	121.6036	39.7605
FRAP	8:30 a.m.	7.75	121.5822	39.7711	4.00	121.5750	39.7760
	9:00 a.m.	17.04	121.5892	39.7706	11.26	121.5829	39.7734
	10:00 a.m.	18.21	121.5889	39.7698	27.83	121.5940	39.7649
	11:00 a.m.	23.22	121.5929	39.7636	39.15	121.6022	39.7599
NBHD	8:30 a.m.	7.54	121.5826	39.7712	5.51	121.5772	39.7737
	9:00 a.m.	16.81	121.5894	39.7713	10.67	121.5818	39.7719
	10:00 a.m.	18.05	121.5890	39.7706	26.56	121.5929	39.7661
	11:00 a.m.	22.41	121.5922	39.7651	38.59	121.6007	39.7621

Table 4
Similarity metrics for comparison of observed and simulated ignited areas.

Case	Time	Distance between centroids (km)		Jaccard Index		S rensen Dice Index	
		At specified time	Average	At specified time	Average	At specified time	Average
	8:30 a.m.	0.49		0.55		0.71	
USFS	9:00 a.m.	0.62	0.66	0.56	0.53	0.72	0.69
	10:00 a.m.	0.74		0.51		0.67	
	11:00 a.m.	0.80		0.49		0.66	
	8:30 a.m.	0.82		0.40		0.57	
FRAP	9:00 a.m.	0.62	0.76	0.53	0.50	0.69	0.67
	10:00 a.m.	0.69		0.55		0.71	
	11:00 a.m.	0.89		0.53		0.69	
	8:30 a.m.	0.54		0.50		0.67	
NBHD	9:00 a.m.	0.65	0.65	0.52	0.54	0.68	0.70
	10:00 a.m.	0.60		0.57		0.72	
	11:00 a.m.	0.80		0.55		0.71	

based on WUI definitions rely on maps that are available to the public. However, the USFS WUI maps only cover the conterminous United States, while the FRAP WUI map is only available for the State of California. In both cases, the maps are several years old and have not been updated recently. Therefore, if a Community Domain needs to be defined for a location where USFS and FRAP maps are not available, or where the existing versions are not as recent as desired, the NBHD method is the simplest to apply. The NBHD method only needs the location of structures, which is typically available. In terms of computational cost, approaches based on WUI maps may require higher computational effort to be generated, while NBHD offers a low-cost alternative that can be expected to be consistent across most (if not all) applications. For these reasons, the NBHD method is identified as the most convenient approach to obtain the Community Domain among the analyzed options.

8. Summary of findings

This study proposed a methodology for seamless simulation of fire spread from the wildland into WUI communities by integrating dynamic wildland fire position input and a WUI-focused fire spread model, namely SWUIFT. A dynamic wildland position input refers to the progression of a fire within the wildland that is continuously updated by an external source, such as wildland fire simulation models or observations (e.g., radar or satellite images). The paper explored the challenges of incorporating a dynamic wildland fire position input into a WUI fire spread model to enable a smooth transition of the fire line from wildland to urban areas. The 2018 Camp Fire incident was used as a case study given the availability of sufficient high-quality data to inform and assess the analysis.

A sensitivity analysis was conducted to assess SWUIFT s performance when simulating wildland-only fire progression, by studying how different initial positions of a static wildland fire input affected the accuracy of the predicted wildland fire rate of spread (ROS) and the fire arrival time at the community. As expected, the analyses confirmed that the initial fire position should be set close to the limits of the community. As a result, the SWUIFT simulation was limited to the extent of an area that described the community s boundaries. This area was called the Community Domain, while the rest became the Wildland Domain.

The legal limits of the Town of Paradise were originally considered as the Community Domain, but it was shown that such limits are not consistent with the contour of the cluster of structures at different locations around the community. Furthermore, legal definitions for community limits are usually open to the interpretation of local authorities and can result in inconsistent Community Domain definitions for future applications. Thus, three additional approaches to describe the Community Domain were analyzed. The first two approaches derived the Community Domain from the existing WUI definitions by the United States Forest Service (USFS) and the California Department of Forestry and Fire Protection s (CAL FIRE) Fire and Resource Assessment Program (FRAP), respectively. The third approach, proposed in this study, described the Community Domain using a neighborhood-based housing density (NBHD) method. The first two approaches depend on WUI maps generated by third parties, while the NBHD only requires the location of structures.

A Three-Domain Solution was proposed to facilitate the integration of dynamic wildland fire position input and SWUIFT. The Community and Wildland Domains were treated to be exclusive with a Transition Domain connecting the fire progression from the Wildland Domain into the Community Domain. Also, potential structural ignitions from firebrands generated from the wildland fire were included, considering the role of spotting on fire spread. Therefore, the Transition Domain, inside which the fire spread was controlled by a wildland fire simulation tool or observations, had SWUIFT partially activated to generate and transport firebrands from the burning vegetation to capture potential ignitions inside the Community Domain.

The proposed Wildland, Transition, and Community Domains, i.e., the Three-Domain Solution, was applied to assess the performance of the different approaches for Community Domain definition (USFS, FRAP, and NBHD). The results validated the use of a Three-Domain Solution and showed that the three approaches resulted in equally acceptable outcomes of fire spread inside Paradise. Nonetheless, the NBHD method stood out when the accessibility to the required inputs and the computational cost were considered. Therefore, the NBHD method was identified as the most appropriate method to be incorporated into the methodology for future SWUIFT simulations.

9. Conclusions

The paper focused on connecting fire spread information in wildland and WUI domains. The study used SWUIFT to simulate fire spread in WUI areas, weather radar data to track the fire line in the wildland, and the 2018 Camp Fire as the case study; however, the proposed methodology can be adapted for general integration of other wildland and WUI fire spread models. The Three-Domain Solution prevents conflicting tracking of fire progression across domains and facilitates a seamless tracking of the fire line from the wildland into WUI areas. The following points should be considered when defining the three domains.

- Boundaries of the Community Domain should be carefully selected with the objective of properly capturing clusters of structures. Existing WUI definitions can be used to inform the boundaries of a community simulation domain, but existing WUI maps may not be up to date, and they may not provide smooth community boundaries. The NBHD method in this study provided acceptable results while computationally efficient.
- The Transition Domain is defined to capture the community s exposure to fire from the wildland. Also, including a Transition Domain provides a means to harmonize available inputs and model features when shifting between Wildland and Community Domains. For example, the Transition Domain should be used to track the firebrands that are generated in the wildland for potential ignitions of structures inside WUI. This implies detailed coordination between the inputs and outputs of involved models in the Wildland and Community Domains.
- Any area outside of the Community and Transition Domains belongs to the Wildland Domain.
- The use of the Three-Domain Solution facilitates the necessary adjustments in spatial resolutions when tracking fire spread in large domains and across wildland and WUI areas.

The methodology that resulted from this study advances the capabilities of WUI fire simulation models, particularly SWUIFT, to be applied for risk assessment as well as real-time and faster than real-time simulations. In the case of pre-event modeling, a predictive simulation can be used to determine the potential impacts of fire in a community and assist with risk assessment and decision-making processes. Real-time simulations with inputs from observations (e.g., radar or satellite) can also help with response strategies.

Author statement

This manuscript is authored by Fernando Szasdi-Bardales, Kasra Shamsaei, Neil P Lareau, Timothy W Juliano, Branko Kosovic, Hamed Ebrahimian, and Negar Elhami-Khorasani. The manuscript is an original research paper and is not under consideration by any other journal. All authors approved the manuscript and this submission.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work is supported through the National Science Foundation s Leading Engineering for America s Prosperity, Health, and Infrastructure (LEAP HI) program by grant number CMMI-1953333. The opinions and perspectives expressed in this study are those of the authors and do not necessarily reflect the views of the sponsor. The National Center for Atmospheric Research is a major facility sponsored by the National Science Foundation under Cooperative Agreement 1852977.

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