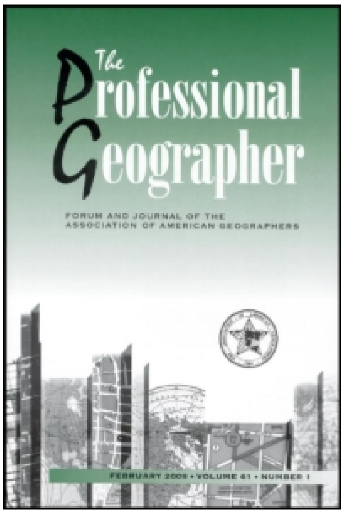

The Professional Geographer
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t788352615

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Zlatina Anguelova[a]; Douglas A. Stow[a]; John Kaiser[a]; Philip E. Dennison[b]; Tom Cova[b]
[a] San Diego State University, [b] University of Utah,

First published on: 09 February 2010

To cite this Article Anguelova, Zlatina , Stow, Douglas A. , Kaiser, John , Dennison, Philip E. and Cova, Tom(2010) 'Integrating Fire Behavior and Pedestrian Mobility Models to Assess Potential Risk to Humans from Wildfires Within the U.S.-Mexico Border Zone', The Professional Geographer, 62: 2, 230 — 247, First published on: 09 February 2010 (iFirst)
To link to this Article: DOI: 10.1080/00330120903543756
URL: http://dx.doi.org/10.1080/00330120903543756

Integrating Fire Behavior and Pedestrian Mobility Models to Assess Potential Risk to Humans from Wildfires Within the U.S.–Mexico Border Zone*

Zlatina Anguelova, Douglas A. Stow, and John Kaiser
San Diego State University

Philip E. Dennison and Tom Cova
University of Utah

Wildfires create a risk to pedestrians traveling through rural areas, because they might not be aware of the presence of a wildfire or its direction and rate of spread until is too late to successfully evacuate. In wildland areas of southern San Diego County, immigrants crossing the U.S.–Mexico border and border security agents are particularly at risk to wildfires. The objective of this study is to develop a framework of analysis and associated tools for examining the combined behavior of wildfires and pedestrian mobility to assess the potential threat of fire to pedestrians in wildland areas. Outputs from a geographic information system (GIS) overlay model for determining potentially dangerous fire zones, the Wildland–Urban Interface Evacuation (WUIVAC) model, and a model of pedestrian mobility in wildland areas were combined to generate wildfire risk to pedestrian maps. The key technical contributions of the study are the development and testing of the pedestrian mobility model and the framework and logic for integrating the results of three GIS-based models. The applied geography contribution is the testing of two scenarios of high risk from wildfires to pedestrians within the U.S.–Mexico border zone of San Diego County, California.

The study results show that the travel times calculated by the pedestrian mobility model appear to be realistic and are affected by the terrain and vegetation characteristics of a study site, whereas the evacuation trigger buffers (ETBs) from WUIVAC are mostly influenced by the wind speed and direction parameters of the FlamMap fire spread model. A moderate fire danger to pedestrians in the most remote wildland locations of the study area is determined. The scenario test results suggest that if a wildfire occurs within 2 km (extreme southwesterly winds) or 6 km (extreme northeasterly wind) of pedestrians in the worst case location within the San Diego border region they would likely not have a sufficient amount of time to reach a nearby safety zone. **Key Words: fire spread modeling, geographic information system, pedestrian mobility, wildfire.**

野火给通过穿越郊外的行人制造了一个危险，因为他们可能一直到太晚而无法成功疏散时才知道野火的存在或它的传播方向和速度。在南部圣迭戈县的野外地区，穿越美国和墨西哥边境的移民和边境保安人员特别易遇到野火的危险。本研究的目的是建立一个分析框架和相关的综合审查野火行为和行人流动性的工具，以评估野火对野外地区行人的潜在危险。本研究把一个决定潜在危险火区的地理信息系统（GIS）叠加模型，一个荒地－城市接口避难（WUIVAC）模型，和一个在野外地区的行人流动模型的输出结果组合起来而生成对行人的野火风险地图。这项研究的关键技术贡献在于，建立和检验了行人流动模型和框架，以及将三种基于地理信息系统的模型结果进行整合的算法逻辑。在应用地理上的贡献在于，在美国和墨西哥的边界地带，加利福尼亚州的圣迭戈县，对两种对行人高风险的野火场景进行了测试。

*Funding was provided by the National Aeronautics and Space Administration, Affiliated Research Center (NCC13–00002) and Research, Education, and Application Solutions Network (NCC13–03007) programs. Officers of the San Diego Sector of the U.S. Border Patrol assisted in obtaining Global Positioning System and digital map data and provided field assistance. Zlatina Anguelova would like to thank Dr. D. Stow, J. Kaiser, Dr. P. Dennison, and Dr. T. Cova for the support and guidance they provided during this research. She would also like to thank her fellow SDSU geography classmates who contributed to the project.

The Professional Geographer, 62(2) 2010, pages 230–247 © Copyright 2010 by Association of American Geographers.
Initial submission, January 2008; revised submissions, August 2008 and January 2009; final acceptance, May 2009.
Published by Taylor & Francis Group, LLC.

研究结果表明，基于行人流动模型计算的行走时间是比较现实的，并且受到研究区地形和植被特征的影响，然而，基于 WUIVAC 估算的撤离触发缓冲区（ETBs）更多的是受到风速和风向的影响，它们被用于 FlamMap 上作为火势蔓延模型的参数。在该研究区，本研究确定了那些发生在最偏远的荒地的，对行人中度危险的火灾地点。场景测试结果表明，如果野火发生在行人所在位置的 2 公里内（极度西南风）或 6 公里内（极度东北风），在圣地亚哥内边境地区，在最坏的情况下，他们可能没有足够的时间逃避到附近的安全区。**关键词：火蔓延模型，地理信息系统，行人流动，野火。**

Los incendios forestales representan un serio riesgo para los peatones de áreas rurales ya que estas personas podrían no percatarse del fuego, o de su dirección y ritmo de expansión, hasta cuando ya sea demasiado tarde para evacuar. Las áreas silvestres del sur del Condado de San Diego son particularmente riesgosas en este sentido para los inmigrantes que cruzan la frontera EE.UU.–México y para los agentes que la vigilan. El objeto de este estudio es desarrollar un marco de análisis y herramientas asociadas para examinar el comportamiento combinado de incendios forestales y la movilidad de los caminantes, a fin de evaluar la potencial amenaza de estos fuegos en áreas silvestres. En el estudio se combinan los datos generados por el modelo de superposición de un sistema de información geográfica (SIG) que determina las zonas de incendios potencialmente peligrosas, por el modelo de Evacuación de la Interfaz Área Urbana-Zonas Silvestres (WUIVAC, por la sigla en inglés), y por un modelo de la movilidad de la gente en áreas silvestres, a partir de los cuales generar mapas de riesgo para la gente por esos fuegos arrasadores. Los aportes técnicos claves del estudio son el desarrollo y ensayo del modelo de movilidad de caminantes, y el marco y la lógica para integrar tres modelos basados en SIG. La contribución en geografía aplicada es la prueba de dos escenarios de alto riesgo para personas por incendios forestales dentro de la zona fronteriza EE.UU.-México, en el Condado de San Diego, California.

Los resultados del estudio muestran que los tiempos de viaje calculados por el modelo de movilidad de caminantes parecen realistas y se ven afectados por las características del terreno y la vegetación del sitio de estudio, en tanto que las alarmas de evacuación (ETBs, por la sigla inglesa) del WUIVAC son influidas más que todo por parámetros de la velocidad y dirección del viento del modelo FlamMap sobre diseminación del fuego. Se determinó un peligro moderado de fuego para los caminantes en las localidades silvestres más apartadas del área de estudio. Los resultados del ensayo de escenarios sugieren que si un fuego ocurre a una distancia de los caminantes de 2 km. (vientos extremados del sudoeste) o 6 km. (vientos extremados del nordeste), en los más desfavorables casos de localización dentro de la zona fronteriza de San Diego, aquéllos probablemente no tendrían el tiempo suficiente para llegar en las proximidades a una zona segura. **Palabras clave: modelo de dispersión del fuego, sistemas de información geográfica, movilidad de peatones, incendios forestales.**

Wildland fire is a type of natural hazard that can be caused by both natural factors and human actions, can be contained if detected in time, and can be predicted to some degree based on knowledge of environmental conditions. Although wildfires are a typical disturbance in many ecosystems (e.g., chaparral shrublands and savannas), they can cause great amounts of destruction to property and can be deadly to people (DeBano, Neary, and Ffolliott 1998; Bond and Keeley 2005). Wildland fires can be especially dangerous to people traveling on foot through rural areas, because they might not be aware of the presence of a wildfire or its direction and rate of spread until is too late to successfully evacuate. These pedestrians will also likely have limited access to shelter from an advancing wildfire. Once a fire has ignited, its behavior is controlled by the vegetation that it encounters, the terrain characteristics of the area, and weather conditions (Pyne, Andrews, and Laven 1996). The same environmental factors (e.g., terrain slope, vegetation biomass and density, and air temperature) influence pedestrian mobility rates and therefore the ability of pedestrians to escape the threat of a wildfire.

Wildland fire is an important aspect of the biological, physical, and human geography of Southern California and northern Baja California (Syphard et al. 2007). Catastrophic fires in the past several decades have burned tens of thousands of hectares of vegetation, destroyed thousands of homes, and taken many human lives in this region (Keeley, Fotheringham, and Moritz 2004). The dry summer seasonal and Santa Ana wind characteristics of the Mediterranean climate, expanding wildland–urban interface (WUI; Ewert 1993), large accumulation of fuel loads due to fire suppression activities, and rugged terrain contribute to the occurrence of devastating wildland fires in the region (Radke et al. 2000). In wildland areas of southern San Diego County, many of these fires are attributed to improperly extinguished campfires left by undocumented immigrants trying to cross the U.S.–Mexico border (Border Agency Fire Council 2003). Considering that there are many border crossers at any given time (McIntyre and Weeks 2002), the likelihood is high that illegal immigrants or border law enforcement officers could be in danger of being overcome by wildfires when on foot within the border zone of San Diego County. To safely evacuate people from a wildfire, it is also important to know how much time it takes them to reach a safety zone. Similar to the concept of "defensible space" (Winter, Vogt, and Fried 2002), a safety zone is defined in this study as a patch of ground of sufficient size and with a limited abundance of combustible fuels, such that a human located within it would not likely be burned or suffer other fire-related health effects.

Several studies have examined the implementation of evacuation orders for populated areas (Kim, Cova, and Brunelle 2006) and the reduction of traffic congestion during vehicular evacuation (Church and Sexton 2002; Cova and Johnson 2002, 2003; Walshon and Marcheive 2007). However, only a few studies have been concerned with pedestrian safety, specifically dealing with firefighter evacuation from wildland areas during a fire (Beighley 1995; Butler et al. 2000; Alexander, Baxter, and Dakin 2005; Cova et al. 2005).

Cova et al. (2005) developed a Wildland–Urban Interface Evacuation model (WUIVAC) that estimates the time required for a wildland fire to travel to a community, person, road, or any protected zone or asset. The product of WUIVAC is a map of evacuation trigger buffers (ETBs) that delineate the point at which an evacuation is recommended should a wildfire cross the buffer, given assumptions regarding weather conditions and evacuation time. The presence of wildfire in the vicinity of an evacuation trigger buffer indicates how long a person or community should have to evacuate before the fire reaches their location (Cova et al. 2005).

To better understand the potential danger from wildfires to pedestrians in wildland areas, it is important to identify specific geographic areas where the risk from wildfire to humans may be greatest (i.e., danger zones). A goal of this study was to develop and test a geographic information system (GIS) overlay model to determine areas of high potential danger from wildfire to pedestrians within the U.S.–Mexico border zone of the San Diego region. Another objective was to develop a pedestrian mobility model (PMM) and to combine the results of the PMM with those from the WUIVAC model (Cova et al. 2005) to generate maps of wildfire risk to pedestrians. Combining the outputs of these models in a logical manner presented a substantial challenge, and developing the framework that enabled this combination of model results is a novel and original contribution from the study. Pedestrian travel times were mapped relative to wildfire evacuation trigger buffers and locations of safety zones, as a means for determining critical locations of wildfire occurrence relative to pedestrian locations. Safety zones were considered to be paved and well-maintained roads, large rock outcrops, water bodies, and recent fire scars (burned within the past five years; Minnich 1983).

The following research questions guided the site-specific aspects of the study:

1. Based on distance to safety zones and fire history, what wildland area within the U.S.–Mexico border zone of the San Diego region presents the greatest burn risk of wildfires to pedestrians?
2. Within the riskiest zone of the study area, what is the greatest amount of time for a person to walk from one safety zone to another (i.e., those safety zones that are most separated in terms of pedestrian travel time)?
3. Based on the locations and times estimated in response to Questions 1 and 2, where would the flaming front of wildland fire have to be located to put such a pedestrian at risk?

Two hypothetical scenarios were utilized to test the integrated modeling framework and formed the basis for maps that were generated to portray wildfire risk to pedestrians. The rationale for testing these realistic scenarios is that they provide border enforcement agents and other "first responders" with strategic planning information on the location and time associated with the greatest risk from wildfires to immigrants and border agents on foot in the study area.

1. A pedestrian (e.g., illegal border crosser) located on a trail moving in a northward direction toward a major road has no communication device or fire protection gear available and no knowledge of the locations of wildfires or safety zones.
2. A pedestrian (e.g., border law enforcement officer) located far away from roads or safety zones has no fire protection gear but does have a communication device and, therefore, knowledge of wildfire locations and nearby safety zones.

Study Area

The study area for this research is defined as the wildland areas of the U.S.–Mexico border zone within San Diego County, California. It extends from the eastern urban edge of San Ysidro (located about 12.5 km west of the Pacific Ocean) 10 km to the San Diego County line in the east. The southern limit is the border and the northern limit is approximately 8 km north of the border, as shown in Figure 1. The terrain consists of foothills, mountains, and valleys. The border study area is characterized by a Mediterranean-type climate with long, dry, hot summers and short, relatively wet, and cooler winters with average precipitation ranges between 250 and 500 mm (Pyne 1984; Zhou, Mahalingam, and Weise 2005). The predominant landscape type is chaparral shrublands, with patchy occurrences of grasslands and woodlands (Hanes 1971). In addition to vegetation, other land cover and land use types include rock outcrops, reservoirs, and rural residential. The study area has a constant flow of illegal crossers and presence of law enforcement officers within the border zone.

Methods

To accomplish the study objectives, three spatially explicit models were implemented individually, and their outputs were combined. The first phase involved the development of a GIS overlay model for locating the area within the border zone of San Diego County that had the highest wildland fire danger. Once this area was determined, the next step was to determine the specific locations where pedestrians associated

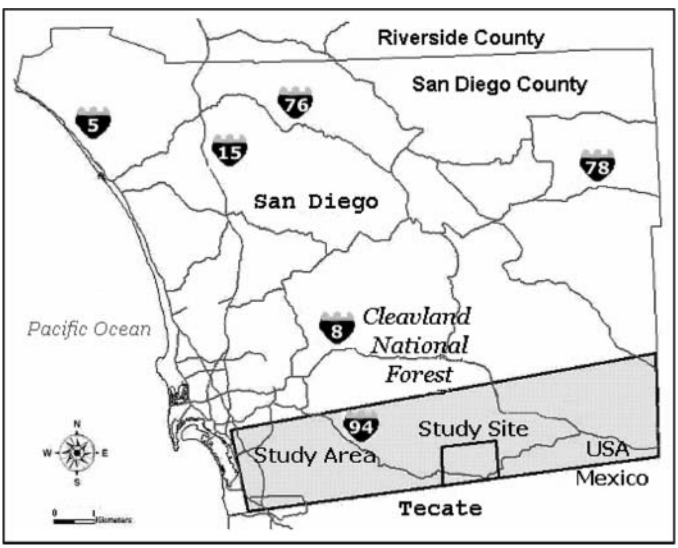

Figure 1 *Study site (small rectangle) determined from geographic information system overlay model as the zone presenting the greatest risk to pedestrians from wildfires within the San Diego–Mexico border zone study area.*

with the two scenarios (i.e., illegal immigrant and law enforcement officer) would be in greatest danger. Based on these locations, the PMM was used to estimate pedestrian travel times to safety zones. These travel times were used in the WUIVAC model as critical thresholds relative to which evacuation trigger buffers were generated. Combining the results of the three models enabled creation of a map of wildfire risk to pedestrians that depicts the likelihood that a pedestrian could reach a safety zone before the flame front of a wildfire at a given location could reach the pedestrian. The entire processing flow is depicted in Figure 2.

GIS Assessment of Pedestrian Danger Zones

The location of the specific study site for scenario testing was determined based on a GIS overlay analysis of extreme wildland fire threat conditions. GIS data layers on fire history (i.e., delineations of previous fire scars and maps of time since last burn), fuel flammability ranking, and distance to and from main roads constituted the criteria for designating zones of high fire threat. Fuel ranks are assigned by the California Department of Forestry (CDF) through a combination of topography, vegetative fuels, and severe weather conditions (wind speed, humidity, and temperature; Fire and Resource Assessment Program [FRAP] 2004).

To delineate the danger zones for the two scenarios, two custom GIS overlay models were developed. For Scenario 1, a raster-based proximity model identified the southernmost point associated with the maximum north–south distance between safety zone locations. This was accomplished by calculating the straight line distances from the southernmost pixels representing departure points near the U.S.–Mexico border to the pixels representing the nearest northward safety zone. The greatest distance path was selected as the most potentially dangerous.

The model also determined the pixel that is located the furthest distance (straight line) away from all surrounding roads and safety zones for Scenario 2, where a hypothetical law enforcement officer has knowledge of fire and safety zone locations and therefore the ability to travel in any direction. To find this location, distances from roads and safety zones were computed, and the pixel with the highest value (furthest distance) was selected as the worst-case evacuation point.

Pedestrian Mobility Model

The PMM was developed to estimate pedestrian mobility rates for wildland areas. This model utilizes the Path Distance function in ArcGIS 9.2 (ESRI) GIS software to calculate the least accumulative cost between adjacent grid cells, while accounting for surface distance, and horizontal and vertical cost factors (Zhan, Menon, and Gao 1993), as shown in Figure 2. PMM employs five travel constraint variables (slope, aspect, roads, trails, and vegetation) for which travel rate percentages are calculated to adjust estimates of pedestrian evacuation timing. A 30-m raster was utilized for data input and modeling. In view of these criteria, the final result of the PMM is a raster data set where a pedestrian travel time is assigned to each pixel in the grid. Based on the predefined objective for this study, pixels of the same travel time were combined to form travel time horizons in fifteen-minute increments.

Slope and aspect inputs to the PMM were derived from a 30-m resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (Farr et al. 2007). Slope values were grouped into five interval classes and aspect values were grouped into ten classes as shown in Table 1 for a northward-traveling pedestrian. A combinatorial AND function was used to combine the slope and aspect data into fifty unique terrain combinations.

Each terrain class was assigned a rate of travel percentage value based on the slope and aspect values (Colorado Hiking 2003). For example, a person travels at full speed (100 percent) if walking on a flat or level slope, regardless of the azimuth direction of the slope. A pedestrian traveling north (e.g., Scenario 1) moves at full speed if walking on any degree slope on an east- or west-facing slope because he or she will be moving parallel to the slope.

To develop a complete rate of travel grid for Scenario 2, where a person can choose to walk in any direction, the DEM image was partitioned into eight 45° sections corresponding to north, northeast, east, southeast, south, southwest, west, and northwest compass directions. For each compass direction, rate of travel values were assigned to the slope and aspect classes,

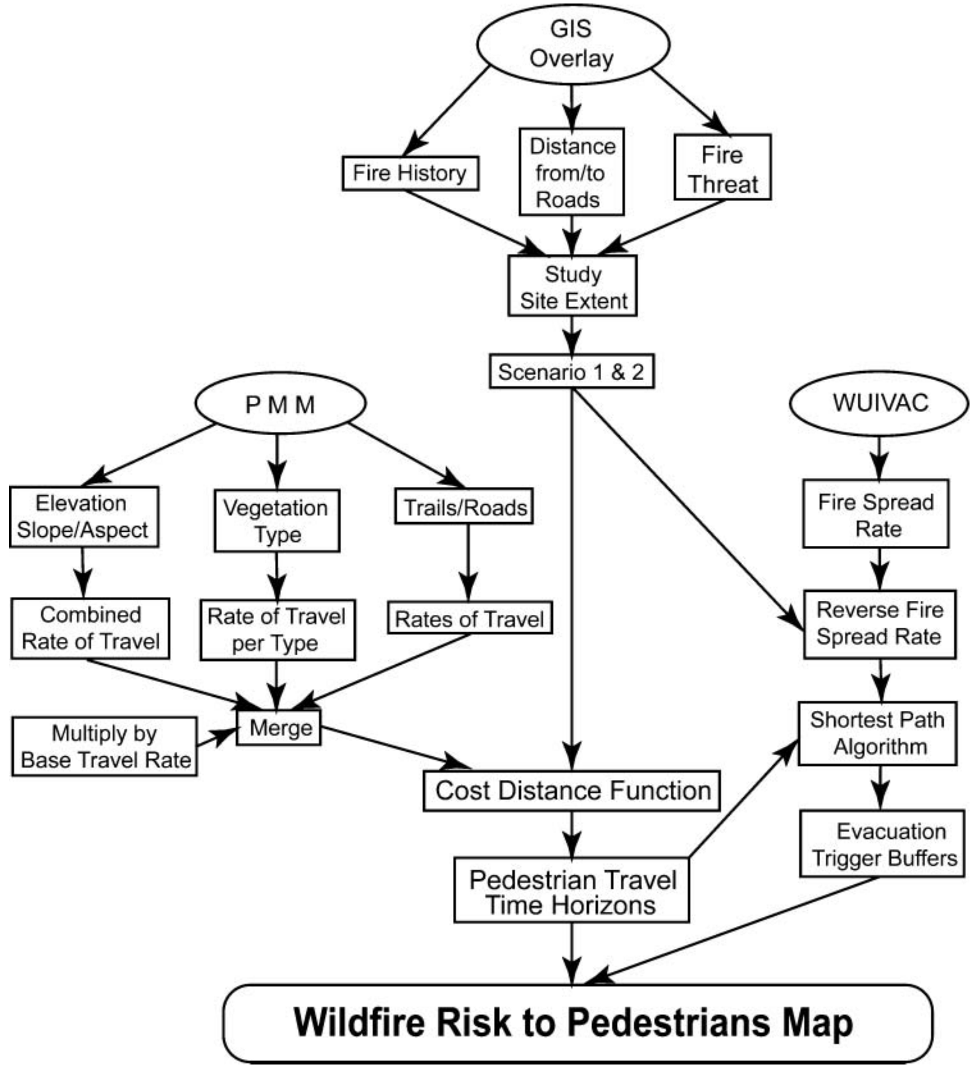

Figure 2 *Study flowchart. Geographic information system overlay model determines the zone representing the greatest risk to pedestrians from wildfires. The pedestrian mobility model was used to calculate travel time horizons for each scenario. Those travel times were used in the wildland–urban interface evacuation model to generate evacuation trigger buffers for both scenarios. The final product of the three models is a map depicting wildfire risk to pedestrians.* GIS = geographic information system; PMM = pedestrian mobility model; WUIVAC = Wildland–Urban Interface Evacuation.

considering the direction of the segment to be the desired direction of movement. A single composite rate of travel raster was formed from the eight slope and aspect rate of travel segments, which was used as an input to the PMM for Scenario 2.

The second type of input data to the PMM is a map representing locations and types of trails and roads, derived through visual interpretation and digitization of 0.3-m resolution color infrared (CIR) digital images that had been generated by scanning 1:20,000-scale

Table 1 *Percentages used for adjusting pedestrian travel rates based on slope and aspect (100 percent full travel speed, 25 percent of the full travel speed, etc.)*

	Aspect									
Slope	**Flat 0°**	**N 0°**	**NE 45°**	**E 90°**	**SE 135°**	**S 180°**	**SW 225°**	**W 270°**	**NW 315°**	**N 360°**
Level	100	100	100	100	100	100	100	100	100	100
Gentle (1°–8°)	100	104	100	100	100	74	100	100	100	100
Moderate (9°–16°)	100	79	104	100	74	44	74	100	104	100
Steep (17°–24°)	100	49	79	100	44	36	44	100	79	100
Very steep >25°	100	25	49	100	36	25	36	100	49	100

CIR aerial photographs. The vector representations of the trails and roads were converted into a raster format having 30-m pixel resolution. Different travel rate percentages were assigned to each road and trail type based on walking speed per land cover type (described later). Road types were classified as A (paved), B (unpaved but well maintained), and C (unpaved, unmaintained roads). The travel rate percentages were calculated by dividing the predicted travel rate into the base travel rate of 70 m/min (4.2 km/hr; Riehen 2001). Predicted travel rate is the estimated walking speed per slope angle and land cover class and the base travel rate is the rate of travel of an average person walking on a flat slope.

Vegetation type and density influence travel rates in the resultant time cost maps, as they can be impediments to people walking off-trail. To account for the impact that the vegetation type and density have on pedestrian travel rates, a Normalized Difference Vegetation Index (NDVI) image was generated from a 30-m spatial resolution Landsat 7 Enhanced Thematic Mapper Plus digital image acquired in October 2005. The NDVI is a function of the reflectance within the red (0.6–0.7 μm) and near-infrared (NIR; 0.7–1.1 μm) wavebands according to the formula:

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red}) \qquad (1)$$

NDVI values have been shown to vary as a function of vegetation type, density, and stature for Mediterranean-type vegetation of Southern California (Gamon et al. 1995; Henry and Hope 1998; McMichael et al. 2004). Because all three of these vegetation characteristics influence rates of off-trail pedestrian travel, image-derived NDVI has the potential to provide a spatially explicit characterization of travel impedance due to vegetation. However, specific relationships between NDVI and off-trail travel rates are unknown and likely complex. We grouped NDVI values into four interval classes that were assigned nominal categories based on likely vegetation community type (barren and grassland, coastal sage scrub, chaparral, and woodland). Each interval class was assigned a travel rate percentage (shown in Table 2), based on simple heuristics established from our field experience. While taking such an "expert" approach is common in GIS modeling, a more empirically based and tested approach to assigning vegetation impedance would normally be warranted. However, in this particular study, the scenarios that were tested involved on-trail pedestrian travel, and the only influence that modeled vegetation impedances had were on the mapped representations of time horizons for nontrail areas (i.e., not on the fire threat results for the scenarios).

PMM was run to calculate the adjusted travel speed rate of a pedestrian, by combining trail or road, vegetation, slope, and aspect layers. This adjusted travel rate grid was multiplied by the base walking speed rate of 4.2 km/h, to find the pedestrian rate of travel per pixel. A cost distance function was used to calculate the overall pedestrian travel time.

The final output of the PMM portrays the time for a pedestrian to walk from a given location to any position in a landscape, by

Table 2 *Rates of travel based on vegetation type and density*

Vegetation type	**Barren and grassland**	**Woodland**	**Coastal sage scrub**	**Chaparral**
Rate of travel	100%	70%	50%	20%

considering slope, aspect, road type, and vegetation as impediments to foot travel. The starting location for the path distance function was based on the danger zones locations associated with the two test scenarios for the zones determined by the GIS overlay assessment of most dangerous fire locations.

Wildland–Urban Interface Evacuation Model

The WUIVAC developed by Cova et al. (2005) was used to assess wildland fire danger in the vicinity of the study site. WUIVAC incorporates a fire spread model component (based on the FlamMap model; Finney 2007) and a mathematical algorithm that utilizes the outputs from FlamMap and terrain data to compute the rate of fire spread in the eight cardinal directions, which are then converted into an asymmetric fire travel-time network. The network is reversed and the shortest path away from an area of concern is calculated using the Dijkstra (1959) shortest path algorithm. The result is an ETB that indicates the shortest time a fire could take to spread to the person, area, or asset at risk.

The first step of the WUIVAC is to calculate fire spread rates using FlamMap for two severe wildfire wind conditions. Several of the input variables in FlamMap (e.g., elevation, slope, and aspect) were the same as those used by the PMM. FlamMap also requires inputs on fuel model types, fuel moisture, canopy cover (based on the fuel models), wind direction, and wind speed. The predominant fuel types found at the study site are classes 1 (grass), 2 (pine/grass), 4 (chaparral), 5 (light brush), 6 (intermediate brush), and 8 (light hardwood) based on the thirteen fuel model types specified by Anderson (1982; FRAP 2005). The canopy cover was set to a constant value of 50 percent, considering that chaparral is the dominant vegetation type in the area (Hanes 1971; Anderson 1982; Minnich 1987). The live fuel moisture content was set to 65 percent for all fuel types based on typical seasonal low values reached in October and November in Southern California (Zhou, Mahalingam, and Weise 2005; Dennison, Cova, and Moritz 2007). The one-, ten-, and hundred-hour dead fuel moistures were based on the relative humidity and fuel moisture readings from the Potrero Remote Automated Weather Station (RAWS) recorded as an average of the extreme readings from the station for the months from June through November 2003, a period of extreme wildfire activity in San Diego County. Wind speed and direction were based on the extreme values recorded at the Potrero RAWS for an eleven-year period from 1996 to 2006 for the months of June through November. This period corresponds to the high fire danger season for Southern California.

Fire spread characteristics (maximum rate of spread and azimuth of maximum rate of spread) were calculated for each cell in the study area rather than from a specific ignition location. Not utilizing an ignition location when calculating fire spread behavior enables generation of evacuation trigger buffers that are representative of fire occurring at any location in the study site under the specified weather conditions.

In the second step of the WUIVAC, the outputs from FlamMap were used to create a network-based representation of the fire spread (Finney 2007) in eight directions (N, NE, E, SE, S, SW, W, NE). Each cell center in the network is connected to its adjacent cell center by arcs representing the minimum travel time of fire spread between cells (Cova et al. 2005).

In the third step, the fire spread network was reversed, and the shortest path (Dijkstra 1959) to all cells within the danger zones for Scenarios 1 and 2 was calculated to create a shortest path tree (Cova et al. 2005). Based on the estimated evacuation time (derived from the PMM), the shortest path tree terminated its spread when the evacuation time value was reached (Cova et al. 2005). With this approach, a buffer was created around each cell of the initial danger zone. For Scenario 1, the danger zone was the evacuation trail and for Scenario 2 it was the location furthest away from all safety zones. Next, a union function was used to combine the buffers corresponding to all danger zone cells into a single composite buffer (Cova et al. 2005). The edge of this buffer delineates a boundary representing the minimum amount of time that it takes a wildland fire to reach the danger zone under given weather conditions. As a result of the shortest path algorithm being used for the calculation of evacuation trigger buffers, the buffers represent the shortest path that fire might travel to the destination cell but not the most likely one (Cova et al. 2005).

FlamMap Evaluation

To determine if the fire spread rates estimated with FlamMap and used to generate evacuation trigger buffers are realistic, FlamMap was run to simulate the behavior of the Cedar Fire that occurred in October 2003 within the San Diego County region and to compare model results to the field-based estimates of fire spread rates. The Cedar Fire was selected for the comparison because it occurred in an area that has similar topography and vegetation cover as the study site used for this research. Furthermore, the weather and fuel conditions during the Cedar Fire were severe, with extremely low humidity, high temperature, strong winds, and low fuel moisture content (Cleveland National Forest 2003). Progression ring maps for the Santa Ana wind-driven sections of the Cedar Fire (shown in Figure 3) were used as the reference data set to delineate the areal extent of the fire spread based on firefighter reports (http://map.sdsu.edu/firenet). Weather data were retrieved from the nearby Pine Hills, Julian, and Goose Valley RAWS stations and used as inputs to FlamMap. Considering that the fire progression data were not recorded systematically (per hour or day) during the fire event, wind speed and direction data that were used for FlamMap simulations were averaged depending on the recorded progression segments.

Integration of Model Results

Although the GIS overlay, PMM, and WUIVAC models can be used as separate tools, integrating results from these models enables the production of a wildfire risk to pedestrians map. The subsequent map shows zones of high fire risk to pedestrians in wildland areas, the time that it takes a pedestrian to evacuate to a safety zone, and the time that it takes the fire to reach the pedestrian's path and the safety zone.

In Scenario 1, a hypothetical illegal border crosser is located at the southernmost point of the study area moving on a trail in a northward direction toward a safety zone location

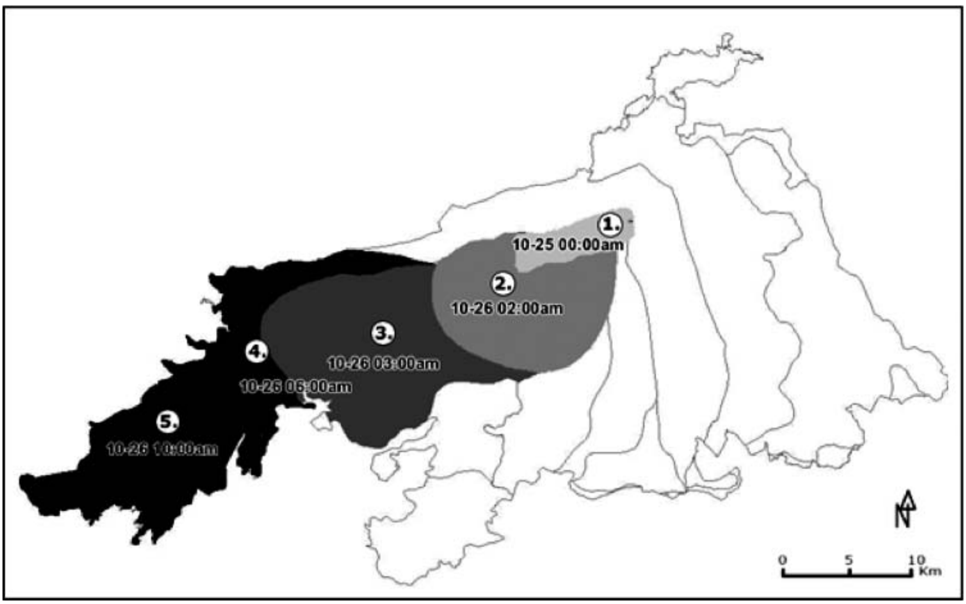

Figure 3 *Cedar Fire progression rings based on firefighters' reports. Ring 1: Fire starts at 05:30 p.m. PST on 25 October 2003 until 00:00 a.m. PST. Ring 2: Fire spread from 00:00 a.m. PST until 02:00 a.m. PST. Ring 3: Fire spread between 02:00 a.m. and 03:00 a.m. PST. Ring 4: Fire spread between 03:00 a.m. and 06:00 a.m. PST. Ring 5: Fire spread between 06:00 a.m. and 10:00 a.m. PST. The rest of the nonshaded rings represent areas burned between 27 October 2003 and 30 October 2003. In these areas the fire was not driven by the Santa Ana winds.*

at the northernmost (furthest away) point. The evacuation timing was calculated from the point of origin for every pixel on the study site. The destination time was based on the time calculated to reach the safety zone cell. The safety zone is assumed to be the northernmost point of the trail, where the trail first intersects a road. The assumption is that an illegal immigrant will only recognize a road of substantial width as being safe enough to avoid being burned or as a means of evacuation (i.e., large rock outcrops or vegetation clearings would not be utilized). The travel route (trail) was divided into sections based on fifteen-minute time horizons (also known as isochrones) estimated by the PMM. Considering that the immigrant border crosser moves in a northward direction, evacuation trigger buffers were calculated first for the entire trail and second for the next section of the trail that starts fifteen minutes away from the origin of the trail, and so on, until the final evacuation trigger buffer was generated for the section of the trail representing the last fifteen-minute time horizon to the safety zone. Combining the models results in such a way helped to determine evacuation trigger buffers for a northward-moving immigrant.

In Scenario 2, a similar approach was used to determine the evacuation trigger buffers and the evacuation timing for a hypothetical border law enforcement officer. The evacuation timing (represented by time horizons) was estimated in the same manner as for Scenario 1. The danger zone located furthest away from safety zones was used in the PMM as a starting location for which travel time horizons were calculated. This point was also used in the WUIVAC model to generate evacuation trigger buffers. The minimum time for an evacuation trigger buffer was set to equal the time that it takes a pedestrian to reach a safety zone. This time was determined by the travel time horizons calculated by the PMM. Considering that a law enforcement officer is not constrained to a single travel direction, it is important to understand how evacuation trigger buffers and time horizons interact. If the time associated with an evacuation trigger buffer is greater than that for a time horizon, an officer can safely evacuate the danger area; if the evacuation trigger buffers time is less than or equal to the time horizon, there is not sufficient time for that agent to evacuate safely.

Results

This section first focuses on the criteria used in the GIS fire danger overlay model for determining the location of the study site. Second, an overview of the steps and procedures used in the fire modeling evaluation process is provided. Finally, the outcomes from combining PMM and WUIVAC model results are discussed in terms of the two hypothetical scenarios.

Greatest Fire Danger Site Location

The specific study site that was delineated by the GIS fire danger overlay model as having the greatest fire risk to a pedestrian in the border zone is shown in Figure 1. The site is located east of the city of Potrero, north of the U.S.–Mexico border at Tecate, south from Cleveland National Forest, and west from Campo. The study site has not burned since 1965 and is classified by the CDF as “extreme fire threat” and “extreme fire threat to people” and has chaparral as a predominant fuel type. Furthermore, this area was identified as having the highest fire danger to pedestrians because it is located in a remote area away from major roads and other types of safety zones.

The GIS fire danger overlay model was also utilized to determine the specific locations of highest fire danger to pedestrians within the study site for testing Scenarios 1 and 2. Figure 4 shows the southernmost location (A) that is furthest away from a northern safety zone (major road) for Scenario 1. This location represents the beginning of a trail at which a hypothetical border crosser could be located and be subjected to the greatest risk to a wildfire. The symbol (B) in Figure 4 denotes the location of the danger zone that is furthest away from all major roads and safety zones for the law enforcement officer in Scenario 2. These two danger zones were used in the PMM and WUIVAC models for the calculations of travel time horizons and evacuation trigger buffer.

Pedestrian Mobility Model Evaluation

The time horizons calculated by the PMM are controlled by the terrain characteristics of the study site and the land-cover types (trails, vegetation, etc.). As can be observed in Figure 5, it is apparent that faster travel times are

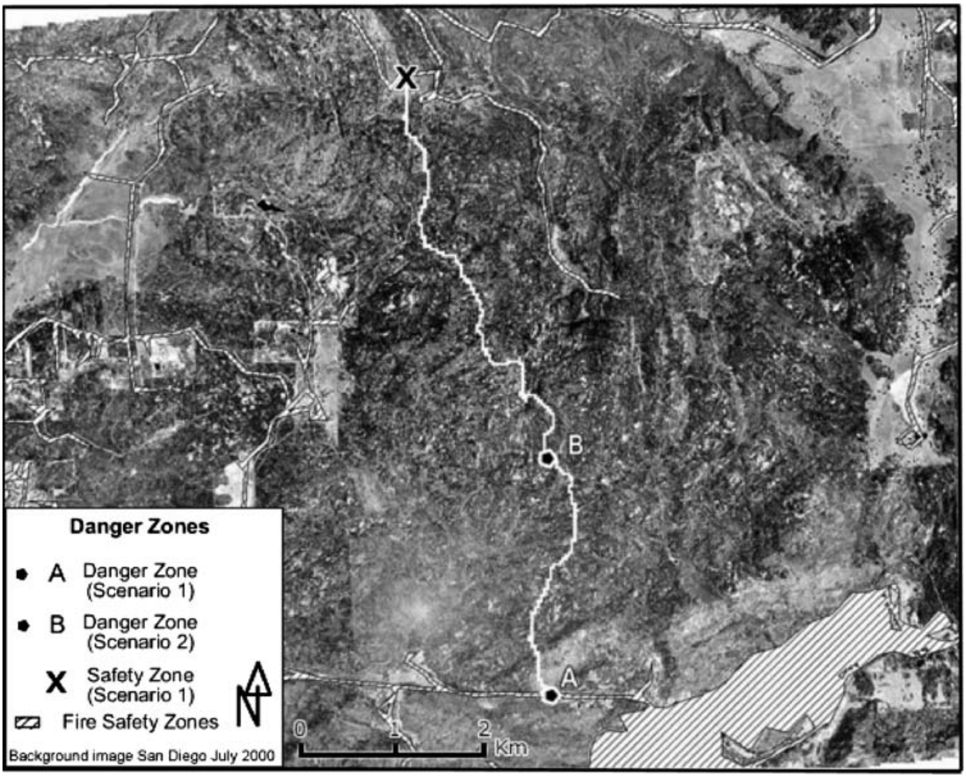

Figure 4 *Depiction of fire threat and safety zones. Scenario 1: A—Southernmost location furthest away from northern safety zone X (at the beginning of the longest south–north trail). X is the northernmost safety zone (major road). Scenario 2: B—Location furthest away from all surrounding safety zones (major roads, large rock outcrops, water bodies, and recent fire scars (burned since 2001). Background aerial photograph: San Diego July 2000.*

associated with the trail network and lower elevation areas. Travel times decrease if a person is to walk off-trail, through vegetation, and upslope.

We evaluated the magnitude of the PMM estimated walking rates by comparing them to travel rates from field measurements and unpublished reports. Because the study area is remote and potentially unsafe, measurements were made on Cowles Mountain within the Mission Trails Regional Park in San Diego County. The study area closely resembles the terrain characteristics and vegetation types at the San Diego–Mexico border study site. Travel rates were calculated for segments of the trail having slope angles similar to those used in the PMM and were measured using a pedometer and a stopwatch. The PMM predicted that a pedestrian walking on a trail with a 0 percent and a 15 percent slope walked at 72 m/min and 43 m/min, respectively. Field measurements at Cowles Mountain were 70 m/min and 40 m/min, respectively, and the "gray literature" suggests rates of 73 m/min for flat surfaces and between 37 m/min and 55 m/min for a 15 percent slope. We conclude that the travel time horizons estimated by the PMM correspond reasonably to the travel rates of an average person.

FlamMap Evaluation

Table 3 shows the wind data that were used for the FlamMap simulations and the comparison

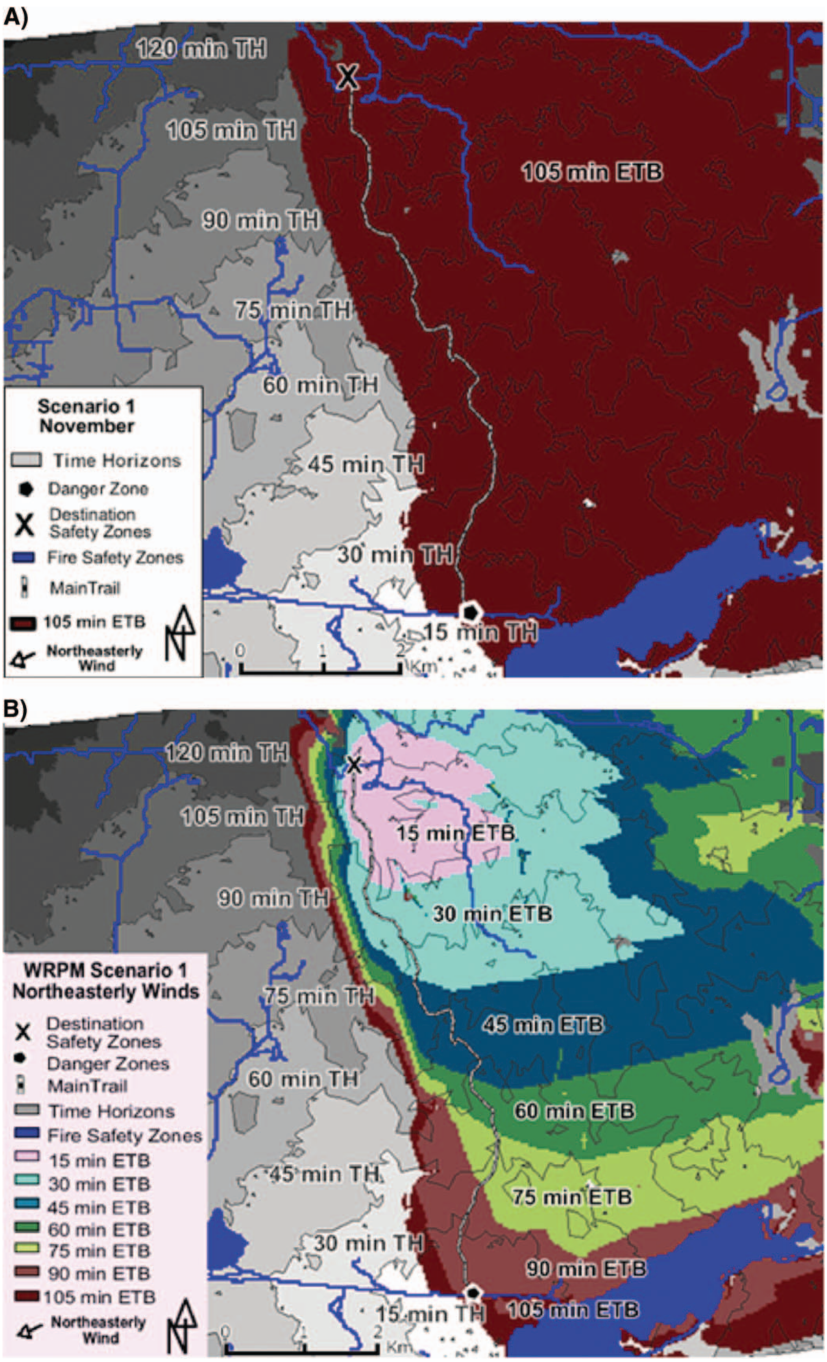

Figure 5 *Wildfire risk to pedestrians map. (A) 105-minute evacuation trigger buffer generated for the entire trail corresponding to the time it takes a pedestrian to reach safety at the end of the trail (northeasterly winds). (B) Evacuation trigger buffers generated per sections of the main evacuation trail (northeasterly winds). (Continued)*

C)

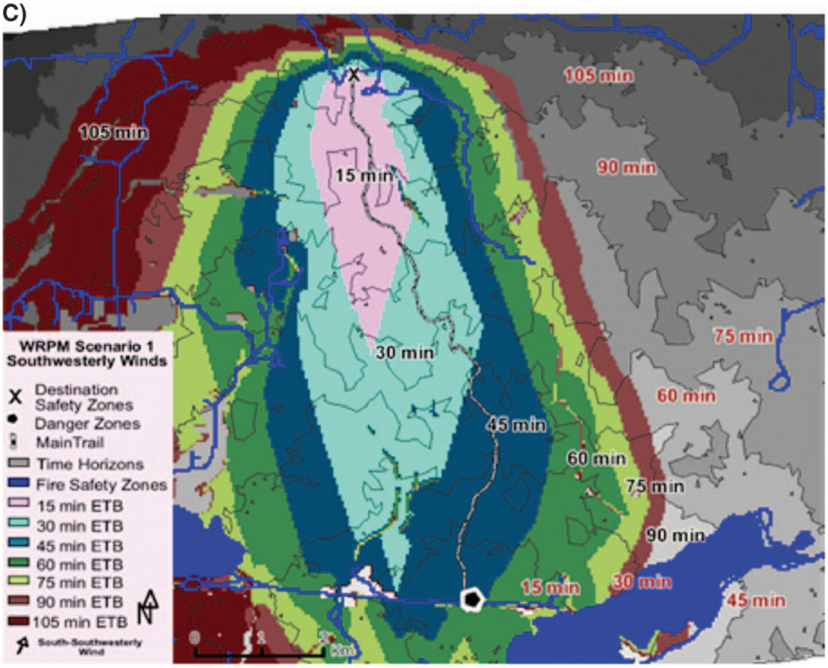

Figure 5 *(Continued) (C) Evacuation trigger buffers (ETBs) generated per sections of the main evacuation trail (southwesterly winds). The time horizons (TH) represent the time it takes a pedestrian to traverse the evacuation trail. WRPM = wildfire risk to pedestrian map.*

between the observed and predicted fire spread rates in the heading direction. The simulated fire spread rates from FlamMap were nearly identical to the reference data for four of the five progression rings.

A large discrepancy between predicted and observed values was recorded for progression ring 3, which represented the fastest moving portion of the Cedar Fire. According to observed fire behavior it took the fire front sixty

Table 3 *Observed and predicted Cedar Fire spread rates*

FlamMap wind data			Fuel moisture			
RAWS location	**Speed km/hr**	**Direction degrees**	**1 hr dead**	**Live herbaceous**	**Cedar Fire observed vs. predicted Spread behavior**	**Fire spread m/min**
					Cedar Fire observed Ring 1	22
Pine Hills	21	90	3	65	FlamMap predicted Ring 1	22
					Cedar Fire observed Ring 2	58
Pine Hills	19	40	3	65	FlamMap predicted Ring 2	54
					Cedar Fire observed Ring 3	172
Julian	60	77	3	65	FlamMap predicted Ring 3	71
Julian	144	77	3	50	FlamMap proposed Ring 3	164
					Cedar Fire observed Ring 4	19
Goose Valley	66	60	3	65	FlamMap predicted Ring 4	19
					Cedar Fire observed Ring 5	69
Julian	79	75	3	50	FlamMap predicted Ring 5	69

Note: Wind speed and direction recorded at Julian, Pine Hills, and Goose Valley Remote Automated Weather Stations (RAWS) on 25 October and 26 October 2003. Data used to validate FlamMap fire spread model as simulation of Cedar Fire spread rates.

minutes to burn to the limits of progression ring 3, which means that the fire would have spread at a rate of 172 m/min. The FlamMap simulated rate based on the highest nearby wind observations was 71 m/min. To assess whether the fire predictions could be altered in a realistic matter and still replicate the fire spread of 172 m/min, northeasterly winds of 144 km/h were required along with reduced fuel moisture values at 3 percent for one-hour dead and at 50 percent for live fuels. Even though the Cedar Fire was triggered by extreme weather conditions it is highly unlikely that the Santa Ana winds sustained velocities of 144 km/h during the Cedar Fire. There is considerable uncertainty in whether the Cedar Fire actually progressed in one hour as far as the progression ring maps suggest, but it is possible that the Rothermel (1972) model on which FlamMap is based is unable to realistically simulate the most extreme fire spread conditions of a Santa Ana–driven fire in dry chaparral vegetation.

Hypothetical Fire Danger Scenarios

Scenario 1 The PMM was executed to determine how long it would take a pedestrian to reach the first northward safety zone. For the calculation of travel time horizons, the southernmost location on the immigrant trail that has the greatest south–north length was used as the starting location in the PMM model. A fifteen-minute time increment was selected for time horizons. The total time to reach the destination safety zone was determined by summing the fifteen-minute horizons (increments) from the beginning of the trail to the safety zone. The worst-case time for an average pedestrian to travel northward between safety zones was estimated to be approximately 105 minutes.

To determine if a northward-migrating border crosser would be able to reach safety before a wildland fire reaches him or her first, evacuation trigger buffers were created relative to the trail on which the pedestrian traveled in the worst-case scenario. The trail was divided into seven sections based on the fifteen-minute travel time horizons generated by the PMM. The trail was segmented to simulate a person moving in a northward direction toward the safety zone. A 105-minute evacuation trigger buffer was first generated for the entire trail length between safety zones, to determine the distance from the trail a wildland fire could be located and still enable the immigrant to reach the nearest northward safety zone. Figure 5A illustrates the 105-minute evacuation trigger buffer for northeasterly (Santa Ana) extreme wind conditions. Subsequent evacuation trigger buffers were generated at fifteen-minute increments following the same logic as the 105-minute evacuation trigger buffer, only for increasingly smaller trail segments, as depicted in Figure 5B. A second set of evacuation trigger buffers was developed for each segment, representing the southwesterly extreme wind conditions shown in Figure 5C.

Scenario 2 The interpretations of the PMM and WUIVAC model results for Scenario 2 differ considerably from that of Scenario 1. The PMM estimates that it would take an officer located at the danger point forty-five minutes to reach the nearest potential safety zone. Based on this travel time, a forty-five-minute evacuation trigger buffer was generated from the danger zone for the southwesterly and northeasterly winds, respectively. Considering that fire spreads faster in the direction of the wind and that the closest safety zone delineated by the forty-five-minute evacuation trigger buffer is located on the wind path, additional evacuation trigger buffers were calculated for the danger zone to determine alternative safety zones. For example, Figure 6 shows that if southwesterly winds are present and a fire starts at a location outside the sixty-minute evacuation trigger buffer, a rescue needs to occur at a location fifty-five minutes away perpendicular to the wind direction. This means that it would take an officer fifty-five minutes to reach safety and the wildland fire sixty minutes to overtake the location of the agent. Figure 7 illustrates that it will take a person fifty-five minutes to reach a safety zone (located to the southeast of the danger zone) and more than ninety minutes for a fire that starts outside the area fanned by northeasterly winds to reach that person. Thus, an officer should have sufficient time to evacuate to the safety zone if a fire occurs outside the ninety-minute evacuation trigger buffer.

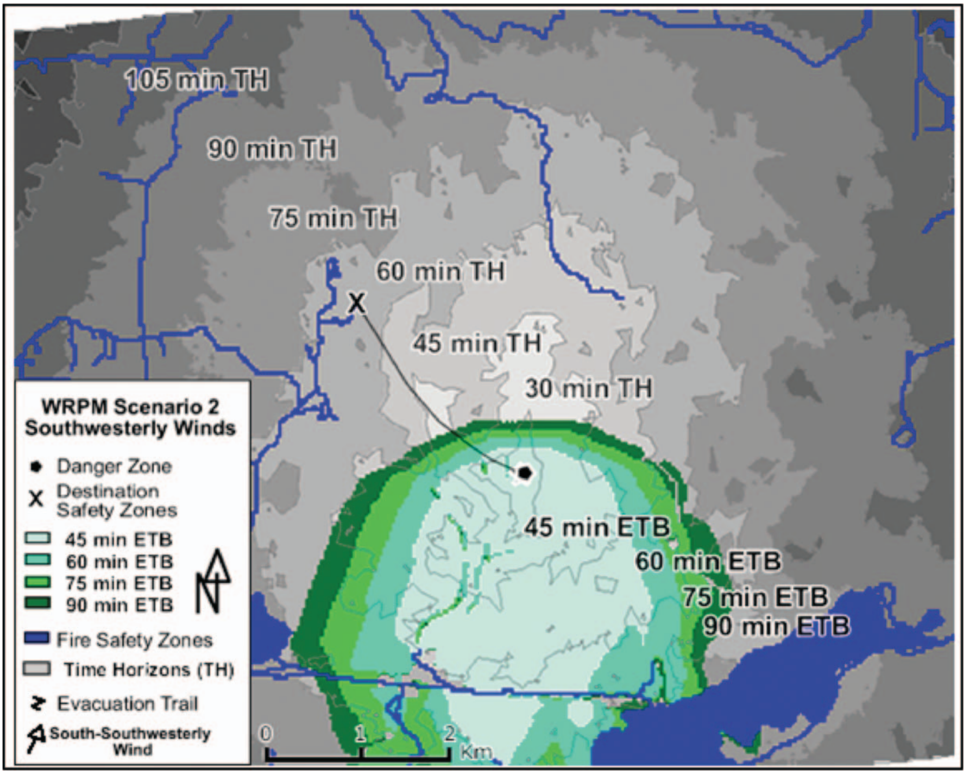

Figure 6 *Wildfire risk to pedestrians map (WRPM). Scenario 2: Fifty-five-minute evacuation travel time (shown by time horizons [TH]) to a safety zone located in a direction perpendicular to the extreme south-southwesterly winds; at least sixty-minute evacuation trigger buffer (ETB) generated for the area to provide the pedestrian safe evacuation.*

Discussion and Conclusions

By combining the GIS overlay and PMM results we determined that for the U.S.–Mexico border zone within San Diego County, the pedestrian travel time for an average person to traverse the longest south–north trail is 105 minutes (Scenario 1). Based on the 105-minute evacuation trigger buffer generated with WUIVAC for severe south-southwesterly and northeasterly winds, the closest locations where a wildland fire could occur relative to the entire trail, such that a northward-moving immigrant with no knowledge of the fire or potential safety zones could safely evacuate, would be 2 km and 6 km away, respectively. Thus, if a wildland fire is further than 2 km (for an extreme south-southwesterly wind) or 6 km (for a northeasterly wind) a pedestrian at any location within the San Diego border region would likely have sufficient time to reach a nearby safety zone.

Because maps depicting wildfire risk to pedestrians are generated by combining the output from the GIS overlay, PMM, and WUIVAC models, and because the models were developed to be spatially explicit (they are not bound to one location), they can be used as a tool for development of fire danger maps for a variety of rural locations and scenarios. For example, the GIS overlay model could be utilized to determine areas of high fire danger and safety zone locations for hikers, campers, and rangers within parks and wilderness areas. The PMM could be utilized to calculate the time it takes an average hiker to traverse the

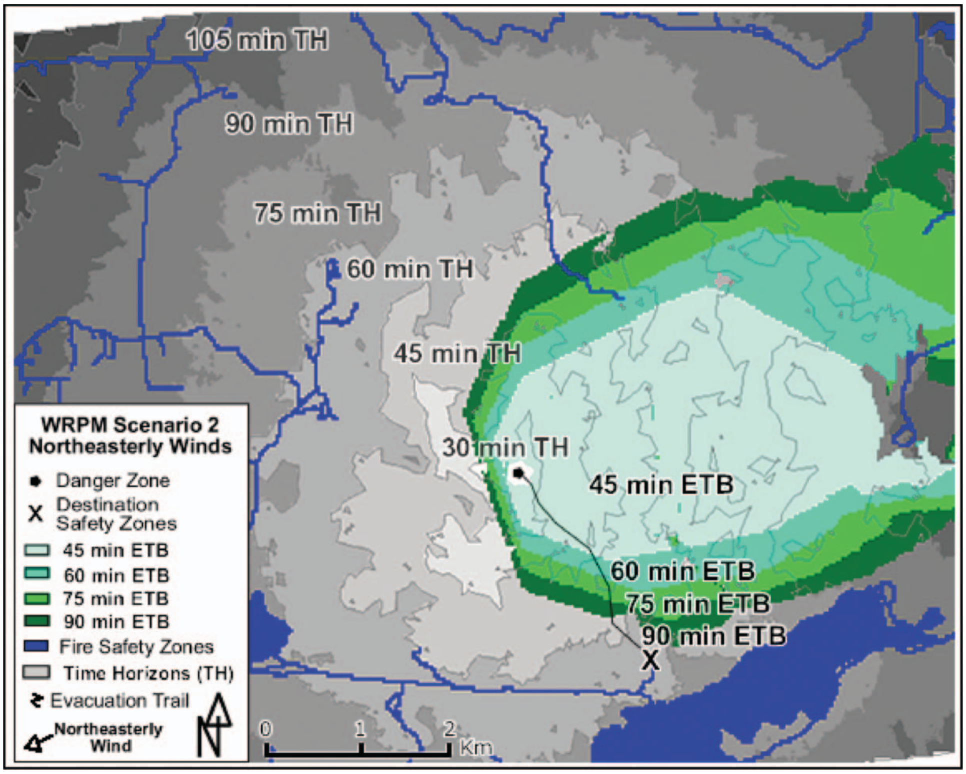

Figure 7 *Wildfire risk to pedestrians map (WRPM). Scenario 2: Fifty-five-minute evacuation travel time (shown by time horizons [TH]) to a safety zone located in a direction perpendicular to the extreme northeasterly winds; at least sixty-minute evacuation trigger buffer (ETB) generated for the area to provide the pedestrian safe evacuation.*

trails at the park and evacuation trigger buffers could be generated for the trails for different weather conditions. However, the most original contribution of the study is the development of the framework and logic for integrating the outputs of these three distinctly different GIS-based models. No previous published studies have examined the potential of geospatial models for quantifying the site-specific wildfire hazard associated with pedestrians traveling across wildland areas.

If maps of wildfire risk to pedestrians were pregenerated for a specific area and weather conditions, they could be utilized by law enforcement officers and fire managers as a reference during safety briefings, for wildland fire evacuation planning, and to educate the population of a rural area. Furthermore, maps of wildfire risk to pedestrians can provide rescue teams and law enforcement officers with general knowledge of high danger zones for which immediate help would be needed to assist pedestrians who might be at risk to a wildland fire.

In the future, maps of wildfire risk to pedestrians could be developed for real-time response to wildland fire events by incorporating current wind and fuel moisture data into the FlamMap model (or other fire spread models) to generate evacuation trigger buffers that are representative of the current conditions. However, such real-time operational usage of the combined models extends beyond the intended and more appropriate utility, which is as a fire danger assessment and planning tool.

Improvements to mapping wildland risk to pedestrians can be accomplished by enhancing the GIS overlay, PMM, and WUIVAC models and conducting a thorough analysis of potential errors and uncertainties in the individual and combined model outputs. Site-specific rules for determining safety zones could be developed. In this study, major roads and recent fire scars were considered as safety zones, but in other areas agricultural fields, water bodies, or large rock outcrops could be considered safety zones. Also, the pedestrian base travel rate used for the calculation of travel time horizons in the PMM could be adjusted to account for varying physiological characteristics of the pedestrians at risk to the wildland fire. Developing and testing relationships between image-derived NDVI and off-trail impedance to pedestrian travel is warranted if the PMM is to be used for estimating travel times in areas void of trails or situations where off-trail travel is more likely. Improvements and enhancements to the inputs and approaches to fire spread modeling would likely yield more realistic estimates of evacuation trigger buffers. For example, incorporation of spatially and temporally varying wind fields should improve the ability to estimate fire spread rates and, therefore, the derivation of evacuation trigger buffers. ■

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ZLATINA ANGUELOVA is a former graduate student in the Department of Geography at San Diego State University, San Diego, CA 92103. E-mail: zuziea@gmail.com. Her research interests include geographic information systems and GIScience, remote sensing, wildfire and fire danger modeling, and vegetation change detection.

DOUGLAS A. STOW is a professor in the Department of Geography at San Diego State University, San Diego, CA 92182–4493. E-mail: stow@mail.sdsu.edu. His research interests include remote sensing, image processing, biophysical geography, geographic information systems, land-use/land-cover change, and Arctic, semi-arid, and coastal ecosystems.

JOHN KAISER is a retired staff member in the Department of Geography at San Diego State University, El Cajon, CA 92020. E-mail: johnkaiser@cox.net. His research interests include geographic information systems and desktop mapping, remote sensing, environmental resource and project management, NEPA/CEQA document preparation, marketing and sales, and physical geology.

PHILIP E. DENNISON is a professor in the Department of Geography at the University of Utah, Salt Lake City, UT 84112. E-mail: dennison@geog.utah.edu. His research interests include remote sensing of vegetation physiology and phenology, imaging spectroscopy, wildfire and fire danger modeling, vegetation and the carbon cycle, natural hazards, and physical geography.

TOM COVA is an associate professor and Director of the Center for Natural & Technological Hazards in the Department of Geography at the University of Utah, Salt Lake City, UT 84112. E-mail: cova@geog.utah.edu. His research interests include hazards and emergency management, transportation and location science, geographic information systems, and GIScience.