WILDLAND FIREFIGHTER ENTRAPMENT AVOIDANCE: DEVELOPING EVACUATION TRIGGER POINTS UTILIZING THE WILDLAND URBAN INTERFACE EVACUATION (WUIVAC) FIRE SPREAD MODEL

by

Gregory K. Fryer

A thesis submitted to the faculty of
The University of Utah
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

The University of Utah

May 2012

The University of Utah Graduate School

STATEMENT OF THESIS APPROVAL

The thesis of ____

has been approved by the following supervisory committee members:

______________________________, Chair ______________
Date Approved

______________________________, Member ______________
Date Approved

______________________________, Member ______________
Date Approved

and by ______________________________, Chair of

the Department of ______________________________

and by Charles A. Wight, Dean of The Graduate School.

ABSTRACT

Wildland firefighters are often called on to make tactical decisions under stressful conditions in order to suppress a fire. They frequently make these decisions based on their gained intuition over time, and also by considering previous specific fire experiences. This assists them in anticipating future fire behavior and developing tactics designed to suppress the fire while avoiding entrapment. These decisions can be hindered by human factors such as insufficient knowledge of surroundings and conditions, inexperience, overextension of resources, or loss of situational awareness. One potential tool for assisting fire managers in situations where human factors can hinder decision-making is the Wildland Urban Interface Evacuation (WUIVAC) model, which models minimum fire travel times to create geographic triggers for evacuation recommendations. Using a range of expected weather conditions and resource configurations, we generated a range of expected trigger buffer outcomes. Our objective was to use these outcomes to illustrate: (a) what spatial uncertainty is inherent in the geographic triggers produced by the range in expected conditions that contribute to fire behavior, and (b) after taking into account uncertainty, whether triggers are likely to be useful for rapid tactical decision-making.

Utilizing 80 different tactical, weather, and fuel condition inputs, we demonstrated the use of WUIVAC for setting trigger points intended for use in planned firefighting operations to ensure entrapment avoidance. These triggers were used to determine when firefighting resources should disengage the fire and evacuate to a safety zone, shelter in

place, turn down an assignment, or reengage and change tactics altogether based on predicted conditions. Using the 2007 Zaca Fire in the Los Padres National Forest, California as a case study, we show that WUIVAC can provide analytically driven physically-based trigger points, and when coupled with intuitive decisions, it can assist in setting triggers for entrapment avoidance and ultimately contribute to firefighter safety.

For Erica and Vena, the two most important people in my life,
who are constantly keeping me grounded, sane,
and most of all happy.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

This long road traveled has only been endurable with the scientific and technical support, personal contributions, and general encouragement and love of many of my friends, family, fellow students, coworkers, advisers, and professors. First, I offer my sincerest gratitude to my mentor and Jedi master Dr. Philip Dennison, who was tremendously supportive throughout my graduate experience, and I am immensely grateful for his knowledge, expertise, and most of all, patience during the course of this thesis process. Phil is the most "dialed" individual I have ever known, and one could not ask for a better advisor. Second, I also would like to express my appreciation to Dr. Tomas Cova and Dr. Andrea Brunelle for their tutelage and advice over the last few years. My time and experience in the department has been enlightening and worthwhile, and I have these three individuals to thank for that.

During my Master's program, I was constantly surrounded by a group of intelligent, caring, and entertaining graduate students; in particular, I am honored with the friendships I've made with Scott Matheson, Julie Miller, Ashley Powell, and Jamie Turrin.

This research was made possible with generous funding provided by NSF grant CMMI-IMEE #1100890. I was also fortunate to have essential, detailed information provided for the 2007 Zaca fire by Jim Smith, North Division Chief on the Los Padres National Forest.

Throughout my career as a wildland firefighter, I have been fortunate and privileged to work alongside some exceptional individuals on Santa Lucia Crew #7, Stanislaus IHC, Cedar City IHC, and Bonneville IHC, and I want to acknowledge those that have helped me hone my firefighting abilities along the way. I've also had the opportunity to work for some of the wildland firefighting industry's most well respected and knowledgeable superintendents, Robert "Doug" Aversano, Greg Overacker, and Ken Henson, from whom I have learned so much, and I am forever indebted.

My parents, Kent and Maureen Fryer, who throughout my life have endured more than any two parents should (two words – treasure map), have been my biggest cheering section. I am thankful to my father bestowing in me the importance of a strong work ethic. To my mother I am thankful for her affection, compassion, and love even when I wasn't always the best son to her. Her tenacious will is something I most admired about her, and is one of her many traits that I try to emulate always. I miss you every day.

Lastly, I would like to thank my wife Erica and daughter Vena. Erica has been my rock and an inspiration throughout our marriage; every success and accomplishment over the last six years would not be possible without her support and love. Vena is the best accomplishment of my life, period.

1 INTRODUCTION

1.1 Wildland Firefighter Entrapment

Wildfire suppression often entails placing firefighting personnel in precarious, life-threatening situations. In addition to the difficulty associated with physically fighting fires (i.e. steep terrain, heat, workload), firefighters are also forced to make tactical decisions which can often be hindered by human factors such as insufficient knowledge of surroundings and conditions, inexperience, overextension of resources, or loss of situational awareness (Alexander & Thomas 2004; McLennan, Holgate, Omodei & Wearing 2006; Putnam 1995; Russo & Schoemaker 1989; Taynor, Klein, & Thordsen 1987; Weick 1993; Weick & Shutcliff 2001). The risk of being trapped or overrun by a wildfire is increased when fire personnel are confronted with these types of barriers (Mangan 2007; Munson 2000).

Since the catastrophic wildfires that occurred in 1910 (Spencer 1958; Pyne 2001), there have been a total of 427 fatalities associated with fire fighter entrapment in the U.S. (NIFC 2010). Entrapment fatalities have decreased significantly since 1995, due in part to doctrinal changes and implementation of risk mitigation guidelines (i.e., L.C.E.S., 10 Firefighting Orders, and 18 Watchouts) (Cook 2004). However, more recent fatality fires such as the 30-Mile (2001), Cramer (2003), and Ezperanza (2006) fires, and "near miss" fires such as the Little Venus (2006), and Angora fires (2007), demonstrate that entrapment risk still exists for fire personnel. Fire frequency has increased in the western United States in recent years, resulting in larger wildfire burn areas (Mckelvey & Busse 1996; Stephens 2005; Westerling, Hidalgo, Cayan, & Swetnam 2006). As a consequence, firefighters, with different degrees of experience and a diverse breadth of knowledge, are asked to make precise and accurate decisions in potentially more hazardous situations. Hence, processes are needed to enable firefighters to assess and standardize their safety concerns, communicate standards among other personnel, and implement those standards in current and planned tactics (Beighley 2004).

One potential tool for assisting fire managers in these situations is the use of protective triggers. A protective trigger is when a predetermined condition is met, firefighting resources can execute a preidentified tactic such as evacuating to a safety zone, sheltering in place, turning down a tactical assignment, or changing tactics altogether and reengage in suppression of the fire based on new or updated predicted conditions (Greenlee, J. & Greenlee, D., 2003). The Wildland Urban Interface Evacuation (WUIVAC) model was developed to derive geographic triggers using minimum fire travel times (Cova, Dennison, Kim, & Moritz 2005, Dennison, Cova, & Moritz, 2007). Using a combination of predicted fire behavior conditions, resource allocations, and tactical assignments for the Zaca Fire on July 5th, 2007, this thesis establishes a quantifiable variability in geographic trigger characteristics within a range of expected conditions. Ultimately, this information is then used to assess the utility of the WUIVAC model for setting trigger points in a realistic fire environment, when it can potentially be utilized in tactical and operational firefighting decision-making processes for the purpose of entrapment avoidance.

1.2 Objective and Research Questions

The first objective of this research was to assess the validity of the WUIVAC model for utilization in future wildfire tactical operations as an evacuation threshold standardizing process. In order to accomplish this, a range of expected weather conditions and resource configurations were processed through the model to create a range of expected outcomes. Our assessment was directed by the answers to the following research questions:

1) What is the spatial uncertainty in geographic triggers produced by the range in expected conditions that contribute to fire behavior?

2) After taking into account uncertainty, are triggers likely to be useful for rapid, tactical decision-making?

Our second objective was to utilize output data for highlighting opportunities for possible modification of the model to better suit more dynamic situations that involve complicated firefighting resource movement and more rapid weather changes, as well as smaller scale uses (i.e., single division of a fire).

1.3 Organization of Thesis

This thesis is organized into six sections, the first of which is the Introduction. Section 2, the Background, is comprised of an overview of policies and procedural changes within the firefighting community, as well as other firefighting tactical improvements made over the last century that have aided in wildfire entrapment avoidance. Secondly, it describes the WUIVAC model itself along with past utilization. Lastly, an explanation of the three methods of attack in fire suppression is provided, with an assessment of the suppression situations for which the WUIVAC model may be most useful.

Section 3 describes the data and methods used in the creation of the simulation scenario used, and explains the processing conducted. Lastly, all metrics used to analyze and validate the WUIVAC model outputs are described. Section 4 is an analysis of all the WUIVAC model outputs and illustrates the variation observed within the trigger buffers, and the effects different resource type evacuation rates have on the outputs. Section 5 is a discussion on the effectiveness of the WUIVAC model for entrapment avoidance, and conclusions are discussed in Section 6.

2 BACKGROUND

2.1 Wildfire Entrapment Avoidance

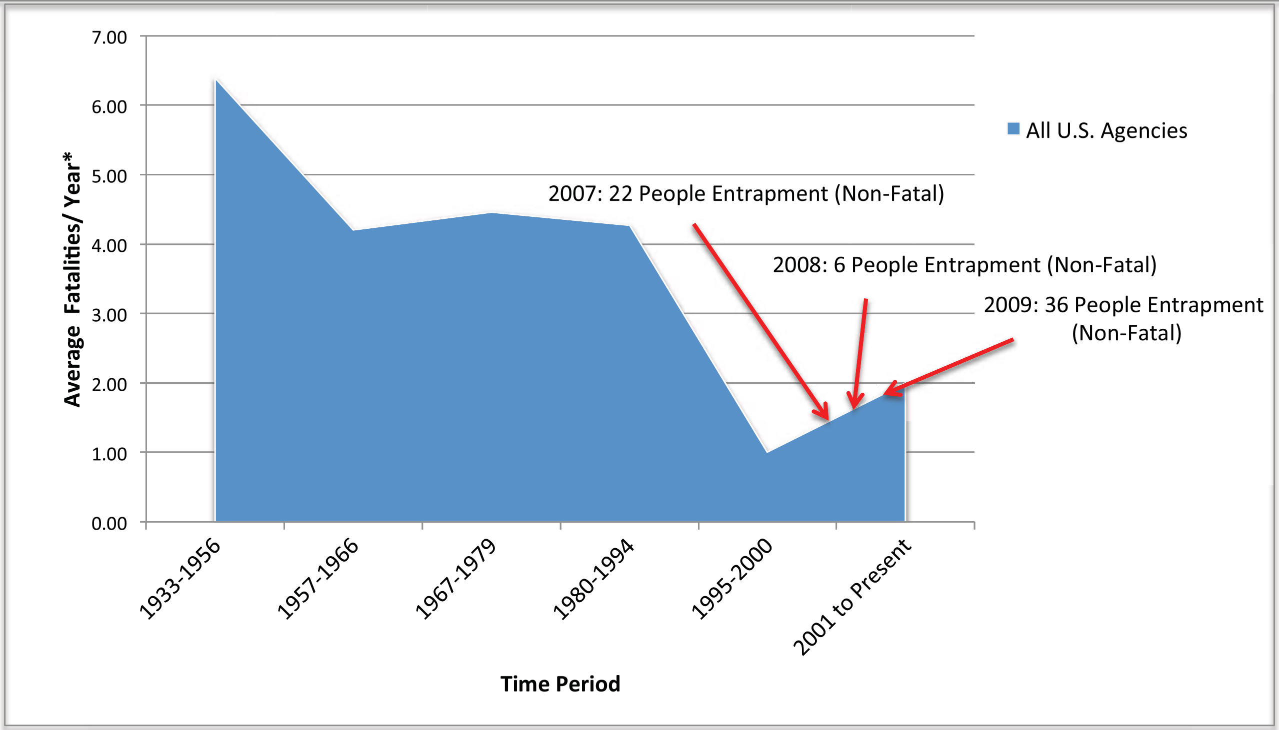
A common threat that firefighters regularly face when encountering a wildfire is the possibility of being trapped or overrun by the fire. Entrapments, shelter deployments, and burn-over fatalities occur when fire personnel are caught in situations where an escape route or safety zone either does not exist or has been compromised by the fire. Inadequate planning, poor situational awareness, or underestimating potential fire spread increases the chance of being entrapped. Most tactical decisions being made in the fire environment rely on precise timing, and avoiding entrapment is reliant on situational awareness, knowing when and where to engage a fire, and most importantly, when to disengage or change tactics altogether.

There have been vast improvements in expertise, knowledge, and effectiveness of fire suppression tactics despite the fact that wildfires have become increasingly difficult to manage. As expertise in fire suppression has strengthened over the years, an understanding of the risks involved in suppression, and how to best mitigate these risks, has emerged. This has been primarily based on previous fatality and near miss fires with an emphasis on entrapment avoidance, and the result has been a significant reduction in the number of fatalities due to burnover type incidents (Cooke 2004).

Since the formation of tactical fire suppression organizations (e.g., Smokejumpers, Hotshot Crews, Civilian Conservation Corps (CCCs)) during the period of the 1930s to the mid 1950s, numerous organizational and doctrinal changes have been established to help prevent entrapments. Cook (2004) illustrates the trends in wildfire entrapment fatalities from 1933 to 2003; more specifically, he addresses the research, reports, initiatives, and policy changes over that time period which contributed to the decline in annual wildland firefighter fatalities, which are explained in further depth below. While there was slow assimilation of these tactical changes into firefighting practices over the last 70 to 80 years, the rate of firefighter fatalities across all agencies ultimately has fallen from 6.39 to 2.0 per year due to improved tactics (1933-2000)(Figure 2.1).

In the 1950s, a task force studying ways to prevent firefighter injuries and fatalities produced one of the first reports during this period, titled the *Report of the Task Force to Recommend Action to Reduce Chances of Men Being Killed by Burning While Fighting Fire* (USDA 1957), which was a follow-up to three fatality fires that had occurred over the previous 8 years. This report fostered the creation and implementation of the "10 Standard Firefighting Orders" and the "13 Situations that Shout Watch Out," which have been updated and nuanced over the last 50 to 60 years as knowledge has been gained from incidents in which an order or a particular situation has led to a fatality, entrapment, or near miss. These "rules of engagement," which are taught to every beginning wildland firefighter in most agencies, are still heavily used today. In 1967 the *Report of the Fire Safety Review Team: A Plan to Further Reduce Chances of Men Being Killed by Burning While Fighting Fire* (USDA 1967) was provided with more recommendations, including improved safety gear, guidelines for constructing fireline downhill, and advocating that portable weather kits be carried on the fireline.

The concept of the common denominators in fatal or near-fatal fires was produced through the research of Wilson (1977), wherein he outlined the four major factors that are



<u>"Rules of Engagement," Doctrines, and Practice Changes by Time Period</u>

1933 - 1956: Development of Smokejumper, Hotshot, and Civilian Conservation Corps (ccc) firefighting programs.

1957 - 1966: Implementation of the "10 Standard Firefighting Orders" and the "13 Situations that Shout Watch Out."

1967 - 1979: Implementation of the Downhill Line-Construction Checklist and improvements in safety equipment.

1980 - 1994: Implementation of the "Common Denominators," and the creation of the Incident Command System (ICS).

1995 -2003: Implementation of L.C.E.S., Risk Management protocol, and "Human Factors" research.

2001 - Present: Implementation of The Thirty-mile Abatement Plan.

Figure 2.1: Entrapment Fatalities per Year by time Period. Adapted from Cooke, 2004.
*Historical Wildland Fire Fatality Data Retrieved from the National Interagency Fire Center (NIFC):http://www.nifc.gov/safety/historical_stats.htm

associated with all fatality fires (e.g. on relatively small fires or deceptively quiet areas of large fires, in relatively light fuels, such as grass, herbs, and light brush). Subsequently, the *Report of the Task Force on the Study of Fatal and Near Fatal Wildland Fire Accidents* (NWCG 1980) was produced with recommendations on how to reduce these types of incidents. Some important developments that came out of the research and findings were the establishment of standardized wildland fire training courses and the creation of the Incident Command System (ICS), which has been replicated and used in many other types of disasters and by a multitude of other agencies (time period: 1980 to 1994). The period from 1995 to 2000 experienced further doctrine implementation, including Lookouts, Communication, Escape routes, and Communications (LCES) (Gleason 2004), and the Risk Management procedures, along with studies that dealt with human factors that contributed to entrapment (Close 2004; Putnam 1995). These "rules of engagement," doctrines, and practices, as Cook (2004) points out, have been the source of debate since their inception, but are still widely recognized as key elements to entrapment avoidance.

Fire behavior research is vast and extensive; however, current research that looks quantitatively at entrapment avoidance is relatively scarce or nonexistent. Butler and Cohen (1998) and Butler and Cohen (2004) investigated the requirements needed for an adequate firefighter safety zone and depicted how it is affected by the average sustained flame length at the edge of the safety zone. They determined a safety zone four times larger than the flame height would be sufficient enough for the fire to have limited or no effect on resources within the safety zone (adjusted for the number of resources). Butler, Cohen, Putnam, Bartlette, and Bradshaw (2000) illustrated effectiveness of various escape routes to safety zones, and Ruby, Leadbetter, Armstrong, and Gaskill (2003) analyzed the effect pack load had on the transit time and physiological processes on a firefighter utilizing an escape route. Dakin (2002) and Baxter, Alexander, and Dakin (2004) measured travel rates for Alberta Type I, II, and III firefighters in four common fuel types. Cheney, Gould, and McCaw (2001) developed the "Dead-Man Zone" concept to represent the area between the handline and fire's edge during a parallel attack, where a firefighter is suddenly in harm's way if a wind change alters the flank of the fire.

Given the valuable yet relatively slow progress in entrapment avoidance, fatality fires nevertheless continue to occur, and they are a result of the same mistakes that the doctrine and policies mentioned above were implemented to reduce. Although there were no fatalities resulting from entrapments during the 2007-2009 fire seasons, there were still 64 cases reported where a firefighter had to deploy a shelter resulting from an entrapment (Figure 2.1). Even personnel with extensive training and years of experience still fall victim to underestimating or not recognizing a situation that forces an entrapment. What is needed is a process that creates an analytical threshold to support intuitive decision-making processes that aid in avoiding entrapment.

2.2 WUIVAC

The difficult and stressful task of making necessary risk mitigating decisions is heightened when important, potentially life-saving choices must be made under dynamic conditions. Occurrence of other unperceived events (i.e. an incident within an incident) that compound a situation can further complicate decision-making (Cova, Drews, Siebeneck, & Musters 2009). As explained by Cova et al. (2009), timing is crucial in making correct and tactically advantageous decisions. There is a threshold at which a firefighting tactic becomes unsafe or too risky to pursue. The threshold for risk differs from firefighter to firefighter, and even the most experienced firefighters may have artificially inflated thresholds (Beighley

2004). This is most evident in tactical operations when fire behavior creates an environment in which the fire personnel are forced to disengage from a tactic and evacuate to a safety zone, deploy their shelters, or change tactics altogether. The correct or incorrect timing of a decision affects the threshold of risk associated with that decision. To help properly assess a risk threshold, firefighters use decision points called triggers, which can be easily identified or communicated, as a way to standardize the threshold (Cook 2003; Cova et al. 2005). Recent advances in fire behavior modeling have made it possible for researchers to computationally obtain these triggers for emergency evacuations or other protective action.

Cova et al. (2005) developed WUIVAC as a warning system for fire managers and communities, which utilizes fire behavior modeling and GIS to derive geographic trigger point "buffers" around a designated protected asset (i.e., home, road, fire resource). WUIVAC uses a three-step process to establish trigger buffers at time intervals corresponding to user-designated evacuation times. The first step incorporates the fire behavior model FlamMap developed by Finney (1998) to determine the rate a fire spreads in eight different directions across a gridded geographic landscape. The second step involves establishing a rate of spread network, where the measured time of a fire's travel from one cell to the next is determined. The final step reverses the spread rate within the network and then uses Dijkstra's (1959) shortest path algorithm to create trigger buffers around the protected asset given a specified amount of warning time (e.g., 1 hour).

The first simulation conducted with the WUIVAC model in a realistic context was done by Cova et al. (2005), in which they simulated a scenario where a fire crew was forced to evacuate from the 1996 Calabasas Fire in Southern California by creating trigger buffers at 15-, 30-, and 45-minute intervals for their location. By demonstrating that the fire crew would have had enough time to evacuate for the modeled triggers, the authors illustrated how a warning trigger could have been useful in this type of situation. However, they do point out several challenges that are inherent in this method, including uncertainty within the model, insufficient, erroneous or dated data collection, and a lack of a standardized trigger point definition among fire resources.

WUIVAC has subsequently been implemented in various other studies. Dennison, Cova, and Moritz (2007) established 1-, 2-, and 3-hour trigger buffers at the community scale in multiple "worst case scenarios" (i.e. maximum winds). Maximum wind speed in 16 different directions was established utilizing 8 years of previous remote automated weather station (RAWS) data to highlight strategically important areas of Julian and Whispering Pines, California. Anguelova, Stow, Kaiser, Dennison, and Cova (2009) incorporated the WUIVAC model in a risk management framework designed to model fire behavior and pedestrian mobility in order to derive maps of wildland fire risk to pedestrians. Their framework was applied to fire hazard to immigrants crossing the U.S.-Mexico border region of San Diego, California. They highlighted geographical areas of vulnerability to wildfires where if a migrant were to cross, they would not have ample time to evacuate. Larsen, Dennison, Cova, and Jones (2011) used data from the 2003 Cedar Fire in California in an attempt to validate WUIVAC-modeled evacuation trigger buffers. By adapting the model to adjust for changes in wind speed and direction, they created dynamic trigger buffers that follow the fire's movement with more precision throughout a designated time. Their WUIVAC trigger buffers allowed adequate time for evacuation and showed the genuine value the WUIVAC model has in community-scale evacuations.

Preliminary research has demonstrated the potential of WUIVAC in situations where the weather conditions and other behavioral aspects are known, and therefore are used to fit the model to realistic outcomes; however, there is a need for validation of the model in more micro-scale situations, such as situations where there is a dynamic, mobile facet (e.g., a protected asset can drive or hike to evacuate an area). Also, further analysis of uncertainty within the trigger buffer outputs may aid in validating the model's usefulness when future conditions can only be predicted, such as in tactical firefighting situations.

2.3 Direct, Indirect, and Parallel Attack

When engaging in fire suppression, there are three tactical methods of attack that firefighting resources utilize: direct, parallel, or indirect. Direct attack involves following the fire's edge and suppressing the flame using water, or construction of a fireline which creates a fuel break between the fire and combustible vegetation, ultimately removing the fire's heat and fuel source. If the fire's intensity is such that "going direct" is not possible, firefighting resources can back away 1 to 5 meters from the fire's edge and construct a fireline, by which the fire runs out of combustible fuel and its intensity is decreased substantially. This method is commonly referred to as parallel attack. It is necessary to note that the modeled scenarios are for "indirect methods" of attack (e.g., firing operations, backfiring, line construction) where a fire resource will be at minimum 5 to 7 meters, and can be up to several kilometers, away from the uncontrolled fire edge, with unburned fuel between the two (Cheney et al. 2001)(Figure 2.2). From this distance a backfiring operation can be conducted, which involves fire personnel lighting the unburned vegetation back towards the main fire with the intent of stopping or changing the direction of the head fire. Hazards associated with direct or parallel attack cannot be modeled with WUIVAC due to the dynamics of the model process, which needs ample distance from the fire. This is due to several issues, including the scale used for fuel inputs into the model and the dynamic nature of a wildfire; therefore, this is an operational consideration in order for the trigger buffer output to have any

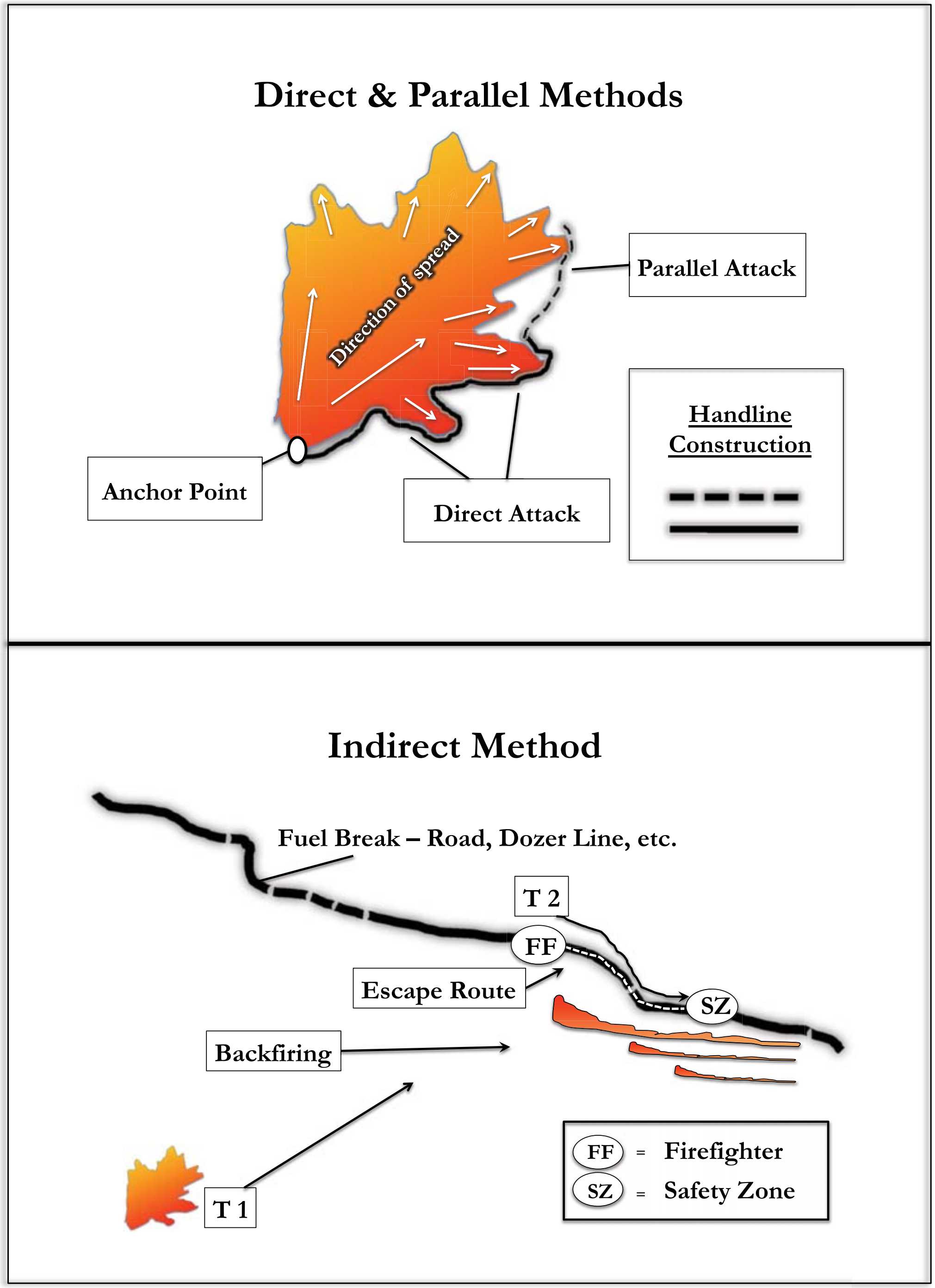


Figure 2.2: The Three Methods of Attack: Direct, Parallel, and Indirect. Also shown, is the relationship Between T1 and T2, as described by Beighley (1995)

usefulness (Cova et al., 2005). Decisions made during direct or indirect methods of attack are often made "on-the-fly" and are reactionary to the fire's spread, but primarily long-term proactive methods (i.e. indirect) work well with WUIVAC.

During the processes of a firing operation, fire personnel not only are in a precarious situation of having unburned fuel between the main fire and their location, but they often find themselves a measurable distance from their designated safety zone (Figure 2.2). In these situations an important standard operating procedure is to establish an escape route – a pre-identified route of travel – used by fire personnel to travel to a pre-identified safety zone where all fire personnel can seek shelter from risk or injury while not being affected by the radiative heat from the flames (Butler & Cohen, 1998 & 2004). Determining an accurate threshold between the time it takes to evacuate fire personnel to the safety zone, and the time it takes for the fire to overtake them before they reach safety, has a margin of success (demonstrated in Figure 2.2). Beighley (1995) first determined a margin of safety measurement, and was further illustrated by Baxter et al. (2004). It is mathematically defined as follows:

$$\text{Safety Margin} = T_1 - T_2$$

where T_1 is the time for the fire to reach the safety zone and T_2 is the time it takes the firefighter to reach the safety zone. A positive safety margin indicates that a firefighter is able to reach the safety zone, while a negative safety margin indicates that the spreading fire entraps a firefighter. Hence, the greater the positive difference between T_1 and T_2, the greater the margin of safety (Baxter et al. 2004).

Since wildfires occur and fluctuate depending on various types of terrain and vegetation that change over a given distance, and under dynamic weather factors that change throughout the day, many different fire spread outcomes may occur in a day's burning period. Using the "margin of safety" concept, it was important to assess whether the WUIVAC model would be useful in determining what the risk threshold for evacuation would be over an operational period for a predetermined indirect method of attack, and also examine whether the trigger buffers may aid in increasing the margin of safety needed when there is uncertainty.

3 METHODS

3.1 Study Area

All data used for this analysis were derived from the 2007 Zaca Fire, which occurred on the Los Padres National Forest, California (Figure 3.1). The fire started on July 4th at approximately 11:00 am (human caused) and eventually grew to 240,207 acres (972 km^2), thereby becoming the second largest fire in California history. The Zaca Fire took 2 months to contain and was finally given a controlled status by the early part of September, requiring involvement from various organizations, including Santa Barbara County Fire, Los Angeles County Fire, Ventura County Fire, California Highway Patrol, and American Red Cross. It took close to 1,000 fire personnel to finally extinguish it (CAL-Fire 2007). Throughout the duration of the fire, besides the obvious threat to life, there were also threats to private entities, including wineries, ranches, and many homes, including pristine public lands and historic structures, as well as numerous wildlife and natural resources.

Contributing to the Zaca Fire's rapid growth were high temperatures, irregular offshore winds, and a preceding 2-year drought, which lowered live fuel moisture and thereby contributed to the extreme fire behavior (Dennison, Moritz, & Taylor 2008). However, of greater significance was the steep, rugged terrain, which allowed for increased fire spread despite the absence of strong winds. This terrain, which fostered unsafe working conditions and restricted access (few roads), forced fire personnel to attempt more indirect

Figure 3.1: Study Area - Zaca Fire (2007)

tactics (e.g., backfiring operations)(Keeley, Safford, Fotheringham, Franklin, & Moritz 2009; McDaniel 2007).

For the purposes of this study, the Zaca Fire provides the necessary information for an analysis of the WUIVAC model. Due to its size and scope, the fire complexities in terms of weather, terrain, and fuel characteristics allow for a more robust assessment of uncertainty in WUIVAC outputs. There are also multiple documented indirect tactical situations that occurred during the fire, allowing us to create a "realistic" simulation to test the model.

3.2 Data

Several data sources, including weather, fuels, fuel moisture, and ancillary data, were utilized in the creation of our scenario for the WUIVAC simulations. All relevant data were processed through the WUIVAC model in the three-step process mentioned above. Steps for creating the scenario and utilizing WUIVAC are described below.

3.2.1 *Incident Action Plan (IAP)*

An Incident Action Plan (IAP) is a central tool used for planning operations within an Incident Command System for any type of disaster relief. It is a detailed written plan provided for the Incident Management Team, and is designed as a way to communicate and transfer important information (e.g., incident command structure, weather forecasts, operational objectives, safety plan, maps) throughout the organization. It is provided to all fire resource managers on an incident, usually in conjunction with their daily briefing. For the purposes of this research, it provides realistic weather and resource data that will allow for a more accurate fire simulation.

The weather data provided for the Incident Weather Forecast portion of the IAP are constructed by an Incident Meteorologist based on up-to-date details about the specific area the fire is located in, and it is what fire personal typically use in the field (although many fire resources take their own weather observations periodically throughout the day to measure more immediate changes). It forecasts maximum temperature, minimum humidity, 20 ft elevation wind speed and direction, and expected changes in these parameters for the entire day.

The IAP also breaks down the operational assignments for a fire into divisional segments for better management of resources (i.e., span of control). Within each division, besides a summary of supervisor names and radio frequencies, there is a breakdown of the number and type of resources and their operational instructions (e.g., construct line, establish safety zones). With this information, a more realistic indirect attack simulation was created to represent tactical situations, based on expected weather conditions and fire behavior, where indirect backfiring operations could occur.

3.2.2 *Wind Direction and Wind Speed Data*

The forecast in the IAP for July 5th called for winds out of the northeast at 4 to 8 mph (6.4 to 12.9 kph) in the morning changing to southwest 6 to 12 mph (9.7 to 19.3 kph) later in the day. Therefore, we utilized these wind directions and speed ranges for our models. To simulate local, topographically driven winds, wind data went through further processing in WindNinja, a computer aided model for simulating terrain effects on wind at small scales (Forthofer 2009).

3.2.3 *Fuel Moisture Data*

Relative humidity (RH), a percentage describing how much moisture is currently in the air relative to the amount of moisture the air needs to become saturated, is vital to the vegetation's availability to burn, affecting the intensity of a fire (Countryman, 1972). RH has a greater impact on smaller and lighter fuels, 0 to 2.5 cm in diameter (1 hr and 10 hr fuels), and a weaker affect on fuels 2.5 cm to 7.6 cm in diameter (100 hr fuels), due to their fast absorption and evaporation properties, thus creating variation diurnally as warming and cooling occur (Pyne, 1996). An IAP is required to have a predicted range in RH for the day for the firefighting resources, and this measurement and range in a fuel's availability to burn is an essential part in fire behavior predictions. However, the FlamMap fire behavior portion of the model requires a dead fuel moisture percentage for 1 hr, 10 hr, and 100 hr fuel time lag classes rather than a RH.

In order to establish the best fuel moisture prediction range for our measurements for July 5th, we utilized the Los Prietos RAWS, which was the closest station to the Zaca Fire at the time of our simulation. We acquired the gravimetric 10 hr fuel moisture low and high averages for the operation period of 07:00 to 19:00 on July 4th to predict the following day's values. The range for July 4th had a high fuel moisture of 8% early in the morning, and a fuel moisture of 5% at the lowest point that day. Due to the previous three day's observations having a consistent range of approximately 5 to 8%, we utilized these high and low percentages for the 1 hr, 10 hr, and 100 hr fuel model inputs for our predicted range in fuel moistures on July 5th, confident that we would have an appropriate approximation. In addition, the live fuel moisture content for the fire behavior model was set at 60% based on typical seasonal values for chaparral vegetation.

3.2.4 *Fuels and Topography Data*

All elevation, aspect, slope, and fuel characteristic (canopy cover, height, base height, bulk density) data were collected and organized through the Landscape Fire and Resource Management Planning Tools (LANDFIRE)(Reeves, Ryan, Rollins, & Thompson 2009; Rollins 2009). LANDFIRE is a multiagency project that provides a framework for universal mapping of wildland fuels, vegetation, and fire regime data at 30 m spatial resolutions. Products that are created by LANDFIRE have been shown to work well with fire behavior models such as FlamMap and FARSITE (Finney 2004; Finney 2006). An ArcGIS tool is provided on their website (LANDFIRE 2010), which allows the user to select an area of interest and upload specific data relatively quickly. The tool then creates a land cover file (.lcp) with the specific ancillary data that the FlamMap fire behavior model requires.

3.3 WUIVAC Processing

Maximum spread rates were calculated for all scenarios, which are defined below, using the FlamMap fire behavior model. The FlamMap software package was designed to approximate fire behavior given constant environmental conditions over a given geographical space (Finney 2006; Stratton 2006). The rate of the fire's spread was calculated using equations developed by Rothermal (1972), and then a two-dimensional spread rate was developed using relationships between spread rate and fire shape (Anderson 1983). These fire behavior calculations were finally used to calculate a rate of spread for each independent pixel over raster topography (Finney 1998). By including our ancillary, weather, and fuel data, the rates of spread and the azimuth of the maximum rate of spread were calculated for the relevant geographic area on the Zaca fire at 100 x 100 30 m pixels (9 km^2). FLAMMAP outputs were then processed by an Interactive Data Language (IDL) program that created a rate of spread for each cell in eight different directions, which were expressed in meters per second. After this process, the output cells were then linked to surrounding cells and adjacent spread rates were combined to form arcs between cell centers representing travel time.

The main output from the WUIVAC model was a trigger buffer around a protected asset (any designated cell) that was based on how long the fire would take to reach that asset given the expected fire behavior (e.g., 15, 25, 45 minutes). This was accomplished by using Dijkstra's (1959) shortest path algorithm, which can be applied to a reversed fire-spread arc travel time network, effectively traveling outward until selected time is reached (i.e. a fire burning in reverse). The result was output trigger buffers of different sizes and shapes, which can be accessed in ESRI's ArcGIS software. Finally, once a network-based representation of the fire-spread rate was constructed, trigger buffers, based on our calculated evacuation times, were developed for the tactical scenarios described in the following section.

3.4 Scenario Creation

Our first objective was to show how well the model performs in tactical decision-making under changing conditions; therefore, it was imperative that we created a tactical firefighting scenario as realistic as possible. Using the Zaca Fire's size (approximately 600 acres) and approximate location on July 5th, as well as resource availability via the IAP for that day, we determined that there existed three possible locations from which indirect pieces of line could be constructed and/or utilized for that day's operations (Figure 3.2: Containment Lines A, B, and C). The operational directive for Division C on the 5th was to

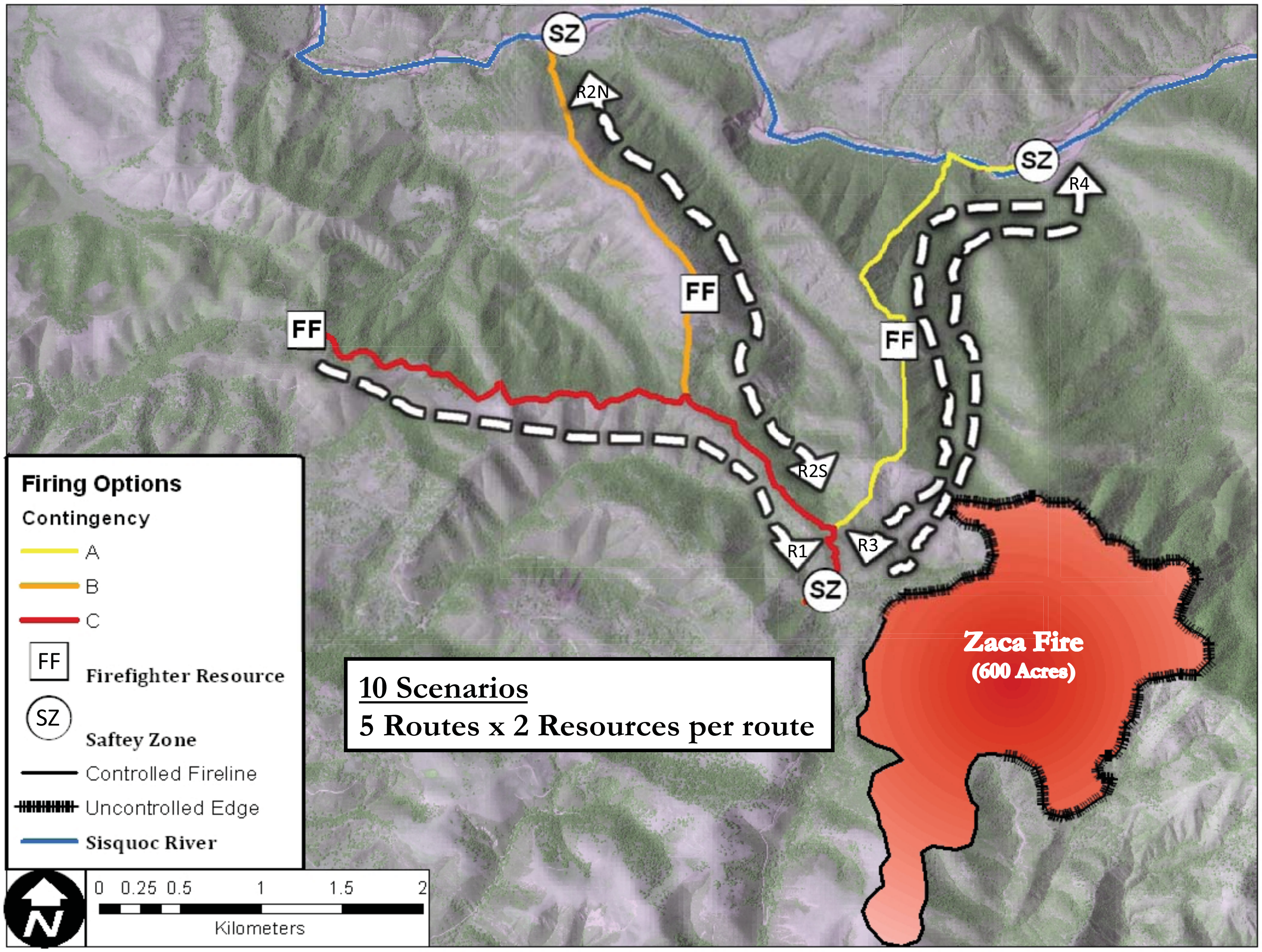


Figure 3.2: Containment Lines A, B, and C for Division C on the Zaca Fire at 600 Acres.

use available resources to "construct line to Division Y." In order to accomplish this using indirect methods, things we considered were: accessibility by firefighters on foot, fire engines (Type 3 – 500 gallons or larger), or "dozers" (D6 or larger) along the entire fuel break, adequate safety zones for personnel to evacuate to (should the fire threaten their safety), and the plausibility of the tactic being implemented in time. Ultimately, we developed three different locations – Containment Lines A, B, and C – as indirect options to construct or improve upon, which would have a high success rate for establishing a fuel-break and subsequently be used to implement a backfiring operation.

Containment Lines A, B, and C were used as the escape routes going to and from each safety zone due to their being the most devoid of vegetation and other debris, which could end up hindering an evacuee. We established five escape route options for the three containment lines (Figure 3.2), and all escape routes and modes of travel are described in Table 3.1. Containment Line C is a U.S. Forest Service road, which is accessible by Type 3 engines and on-the-ground firefighters traveling by foot. Containment Lines A and B utilize undeveloped, often steep ridgelines which have to be improved with dozers, thus being only accessible by foot with no engine support.

For both Containment Lines A and B, adequate safety zones are located at both the north and south ends of their lines. Containment Line C, however, has only one safety zone located to the south and thus only one directional option for evacuation, which we designated R1. Since there are two safety zone options for both Containment Lines A and B, we created two different route scenarios. For Containment Line B, we split the line equally in two and created routes R2N and R2S. For Containment Line A, one route (R3) extends from the most southern safety zone to the most northern, and another route (R4) extends from the northern safety zone to the south.

Table 3.1: The Five Evacuation Routes and Modes of Travel for Each Containment Line.

	Route	Escape Route Type	Modes of Travel	Containment Line
1	R1	U.S. Forest Service Road	Engine, On Foot	A
2	R2N	Dozer Line	Dozer, On Foot	B
3	R2S	Dozer Line	Dozer, On Foot	
4	R3	Dozer Line	Dozer, On Foot	C
5	R4	Dozer Line	Dozer, On Foot	

3.4.1 *Evacuation Travel Rates*

A rate-of-travel was determined for each of the three transportation types at a 0 percent slope: on-foot (OF) = 90 m/minute, in an engine (EG) = 650 m/minute, and in a dozer (DZ)= 65 m/minute. We assumed that an engine could travel at 650 m/min on a forest service road and still have the control to maintain its safety. We based the on-foot rate on the Baxter et al. (2004) study of firefighter mean travel rates for a Type III crew on short grass while carrying both a pack and tool. They recorded a mean rate of 93 m/min, which we rounded down to 90 m/min for a more conservative evacuation time. For the dozer, we estimated that it would travel 25 to 30% slower on flat ground than someone on foot. To adjust the travel rate for changes in terrain, Tobler's (1993) Hiking Function and the Path Distance tool in the ArcGIS software were used to create a realistic travel time for each mode of transportation back to the designated safety zone for each raster cell along the escape route. All times were rounded up to the nearest whole number.

For our scenario, the trigger buffers need to account for the firefighting resource at any point along the designated escape route. Thus, our five escape routes were used to create five rasterized masks for extraction of evacuation times. As indicated in Figure 3.3, the value in each cell represents the travel time needed to reach the safety zone. Each cell is treated as a protected asset in order for a buffer to be calculated for each cell based on its travel time. A union is then formed of all buffers created for each cell on the entire escape route. The resulting 10 buffers are designated as follows: Route 1 Engine (R1EN), Route 1 Foot (R1FT), Route 2 North Foot (R2NFT), Route 2 North Dozer (R2NDZ), Route 2 South Foot (R2SFT), Route 2 South Dozer (R2SDZ), Route 3 Foot (R3FT), Route 3 Dozer (R3DZ), Route 4 Foot (R4FT), Route 4 Dozer (R4DZ). Figure 3.4 illustrates the relationship the relative max travel times for each route and mode of transportation.

3.4.2 *Model Inputs*

For our July 5th study area on Division C we have eight different fire behavior scenarios that represent the predicted range and variability of conditions for that day (Table 3.2). For dead fuel moisture (FM) we have a high value of 8% and a low value of 5%. Wind direction is predicted out of the northeast (NE) and the southwest (SW) based on the IAP. For the NE wind direction there is a wind speed range of 4 mph to 8 mph, and for the SW wind direction there is a wind speed range of 6 mph to 12 mph. As specified above, we established five evacuation routes and two travel methods for each route for a total of ten tactical scenarios. Including the ranges of wind and RH inputs, 80 scenarios that span the range in tactics and predicted fire behavior conditions for our operational period.

These final 80 scenarios were processed through the WUIVAC model to assess the difference between the trigger buffers (Figure 3.5). We used the following metrics to calculate the variation:

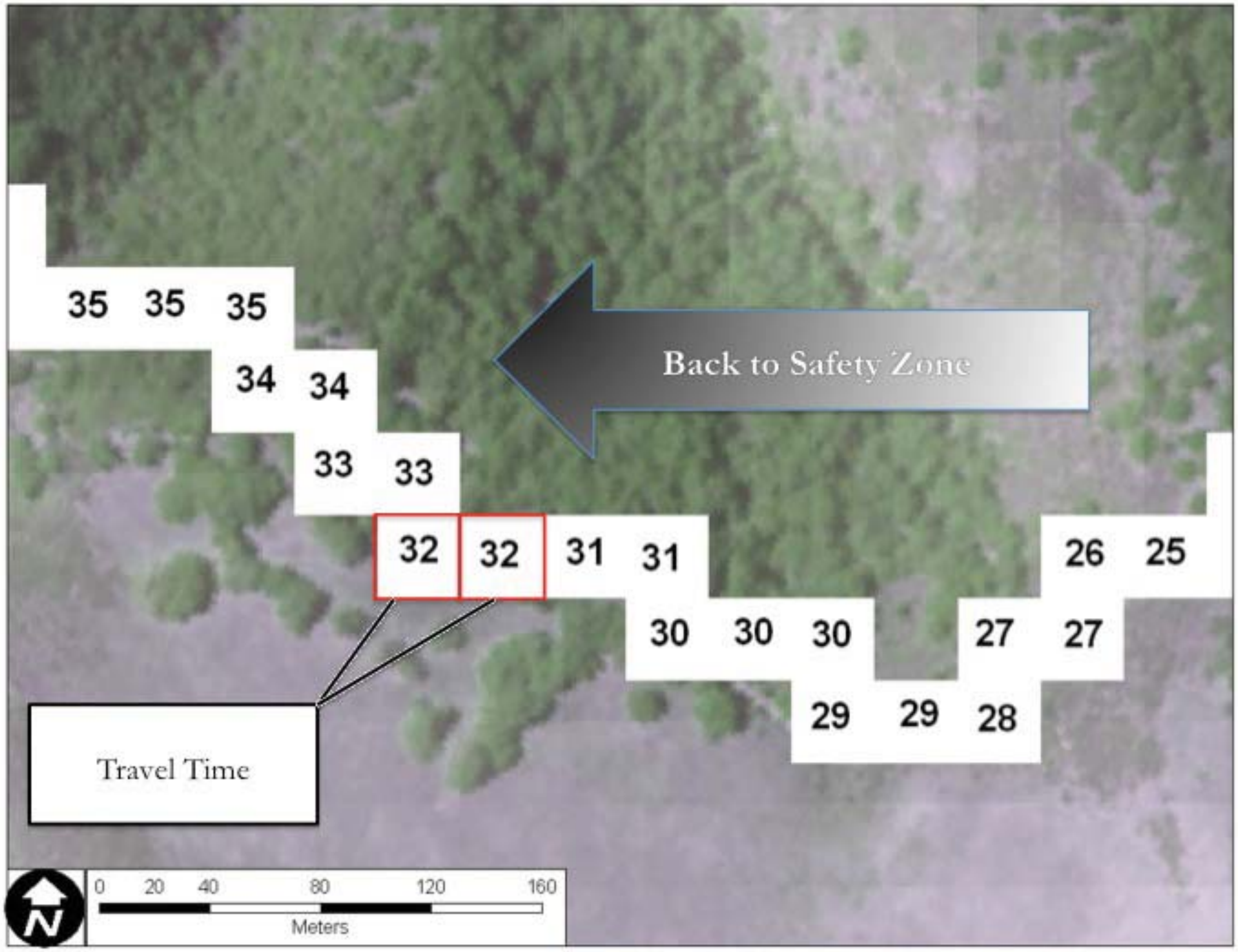


Figure 3.3: Example of an Escape Route where Each Cell Represents Travel Time Back to Safety Zone.

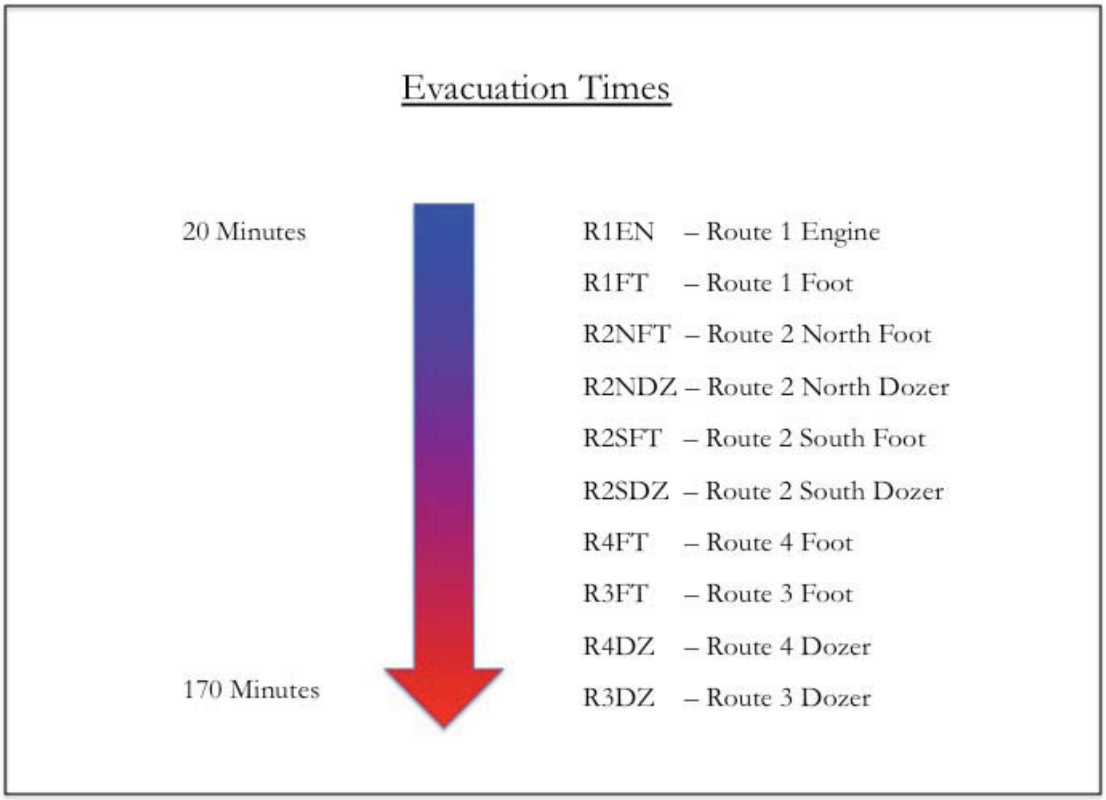


Figure 3.4: Comparison of Route Travel Time.

Table 3.2: Eight Weather and Fuel Inputs

Weather and Fuel Inputs	
1	FM5 - NE - 4mph
2	FM5 - NE - 8mph
3	FM5 - SW - 6mph
4	FM5 - SW - 12mph
5	FM8 - NE - 4mph
6	FM8 - NE - 8mph
7	FM8 - SW - 6mph
8	FM8 - SW - 12mph

1. Area within each buffer

2. Maximum, minimum, and mean distances between the protected resource and the edge of the buffer

3. Mean difference in the distance between different buffers

4. Distance measures in specific directions

5. Distance measures for different resource types

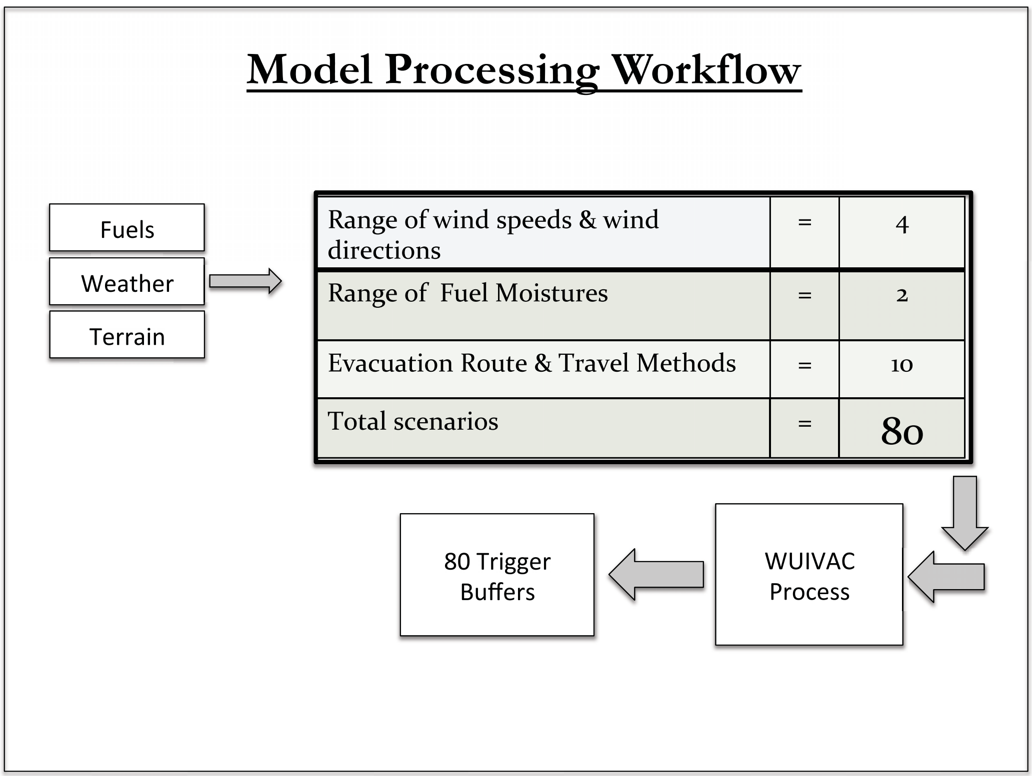


Figure 3.5: Workflow Process for our 80 Tactical and Fire Behavior Condition Scenarios.

4 RESULTS

Once all 80 tactical and fire behavior condition combinations were processed, the resulting output geographic trigger buffers (Figures 4.1 through 4.8) were used to calculate statistics. Qualitative and quantitative analyses show discernable patterns between scenarios, and these patterns are varied depending upon the input conditions. This was expected, and the observed variation between trigger buffers demonstrates the usefulness of trigger buffer application in tactical situations involving firefighting resources. Total area, direction, and mean and max distances of the resulting trigger buffers were measured to assess variability, and subsequent uncertainty.

As illustrated in Figures 4.1 through 4.8, a comparison between the 5% and 8% dead fuel moisture inputs for each scenario shows the total area of an escape route's trigger buffer increases as fuel moisture percentage is decreased. Wind speed and direction also have a strong influence on a trigger buffer increasing in area, but wind speed, rather than wind direction, dictates where the majority of the trigger buffer's area resides. Also influential in dictating trigger buffer area is a route's evacuation time. The total area of a buffer increases as time needed to evacuate increases (i.e. evacuation time: R1EN = 20 min vs. R3DZ = 175 min). As expected, when a resource travels toward the safety zone, a larger portion of the trigger buffer area was present around the safety zone to allow the resource safe travel from the farthest point out.

R1FT

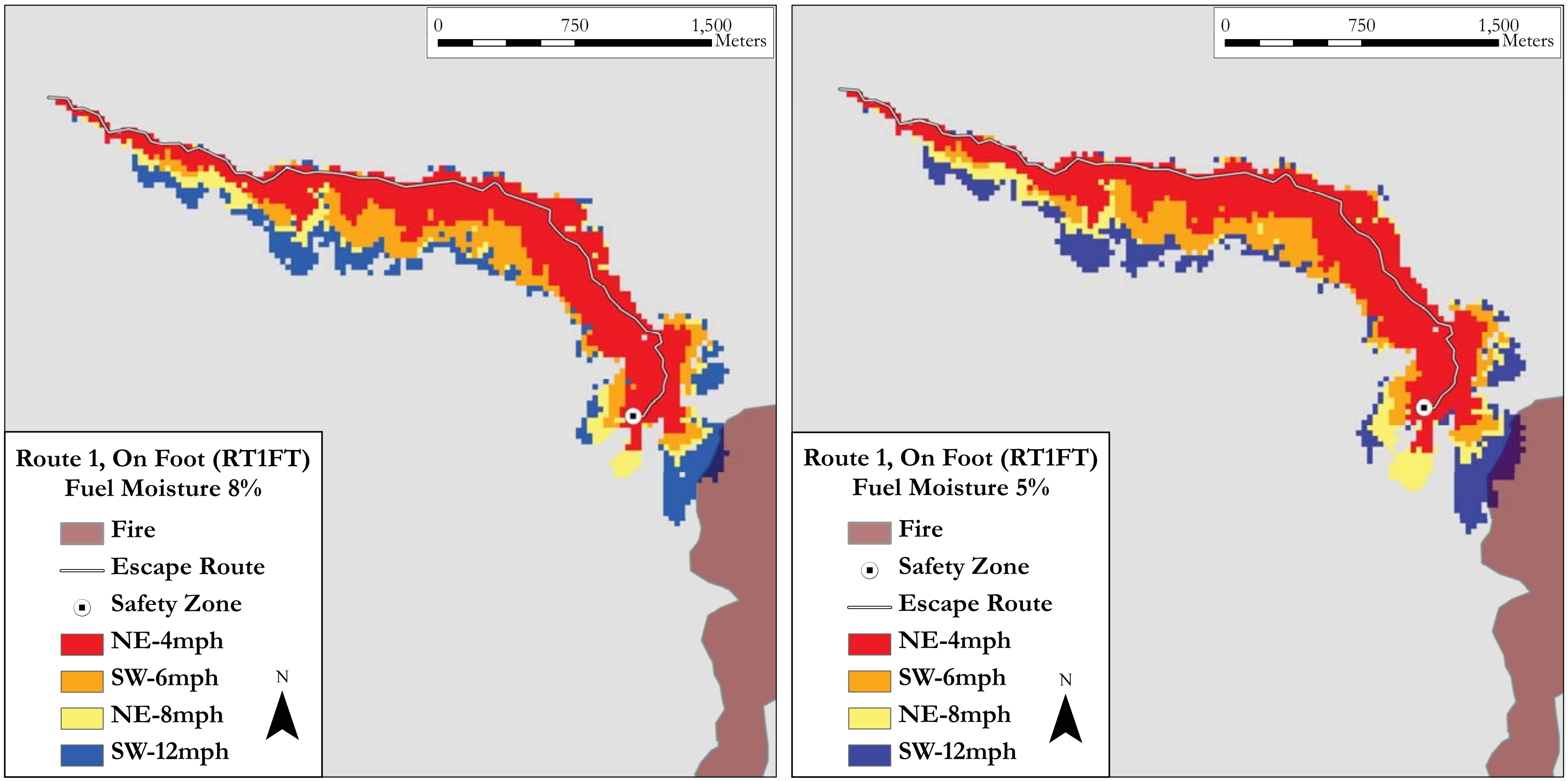


Figure 4.1: Trigger Buffers for R1FT at Fuel Moisture 5% and 8%

R1EN

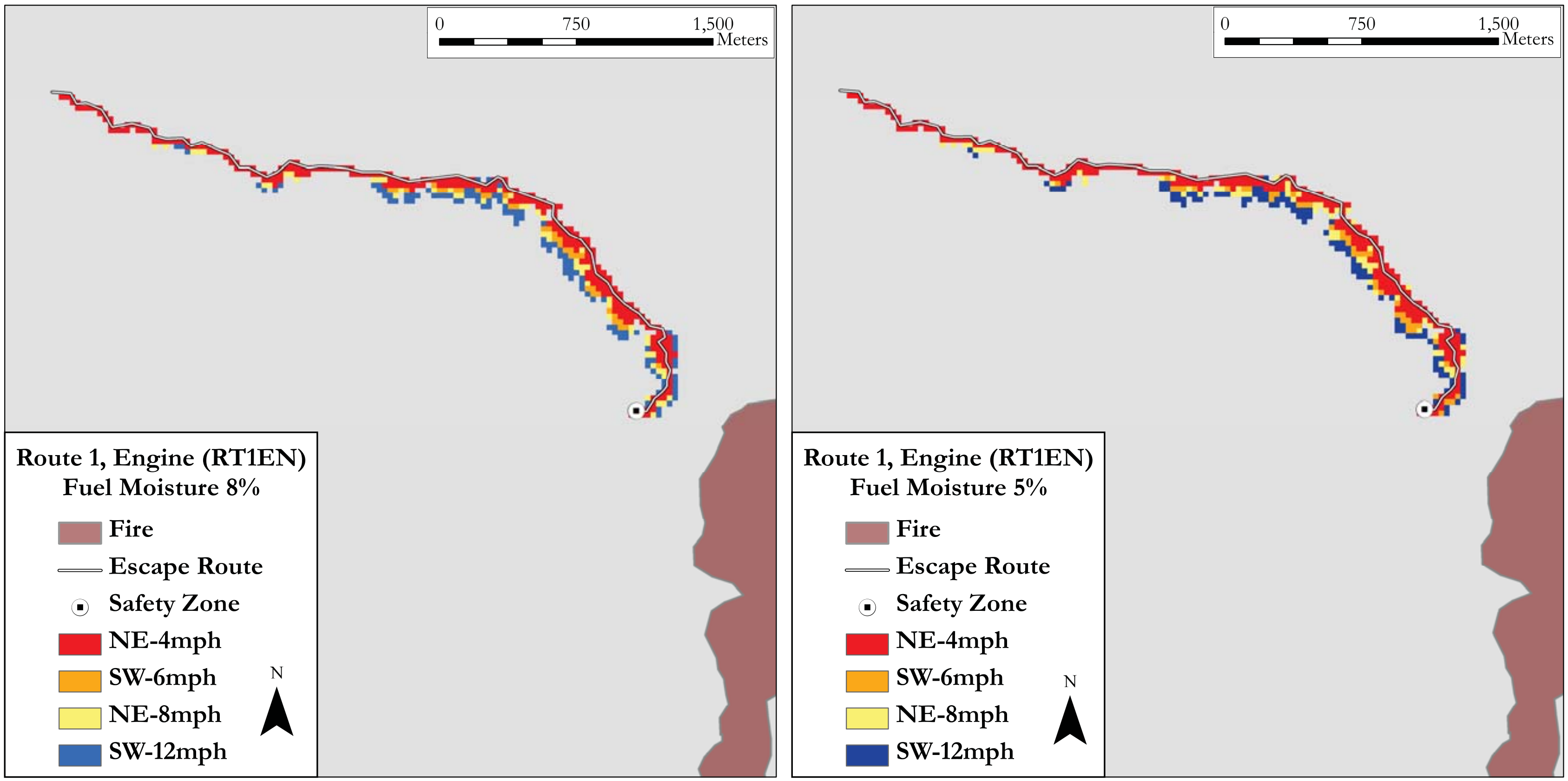


Figure 4.2: Trigger Buffers for R1EN at Fuel Moisture 5% and 8%

R2NFT & R2SFT

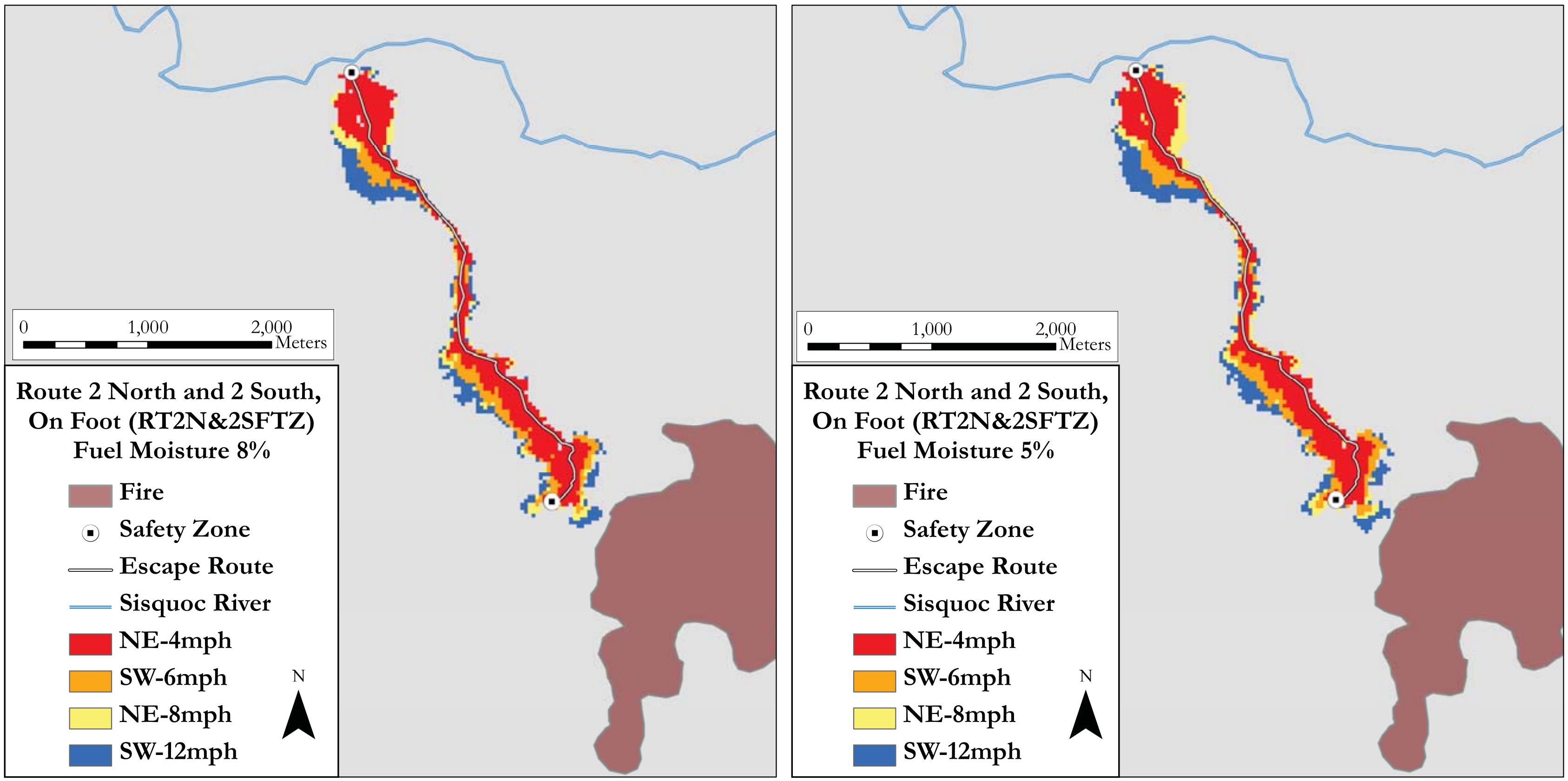
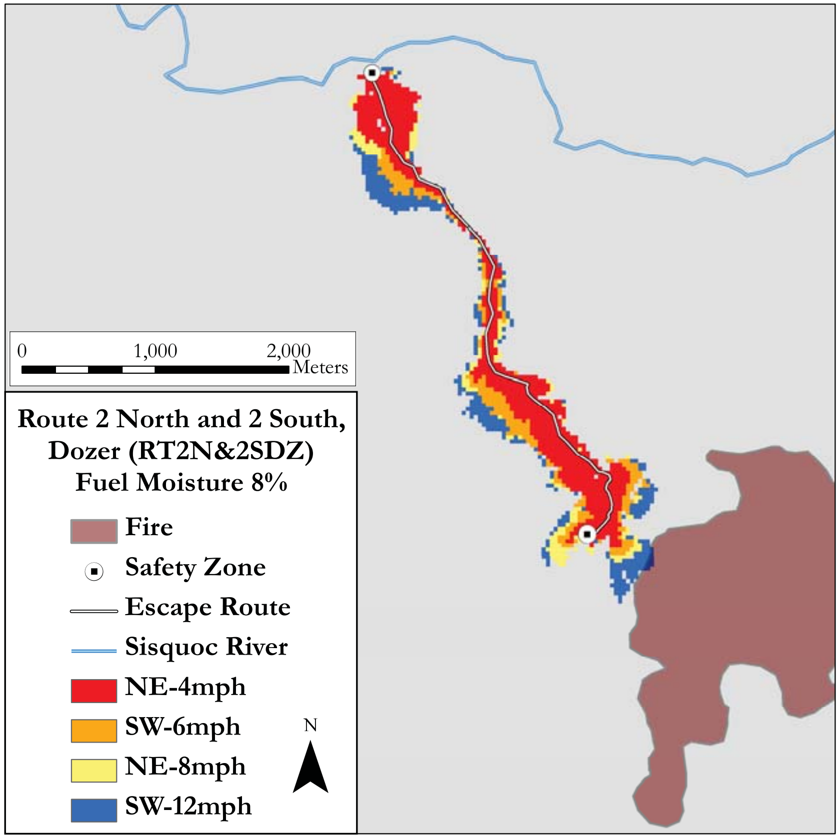


Figure 4.3: Trigger Buffers for R2NFT & R2SFT at Fuel Moisture 5% and 8%

R2NDZ & R2SDZ



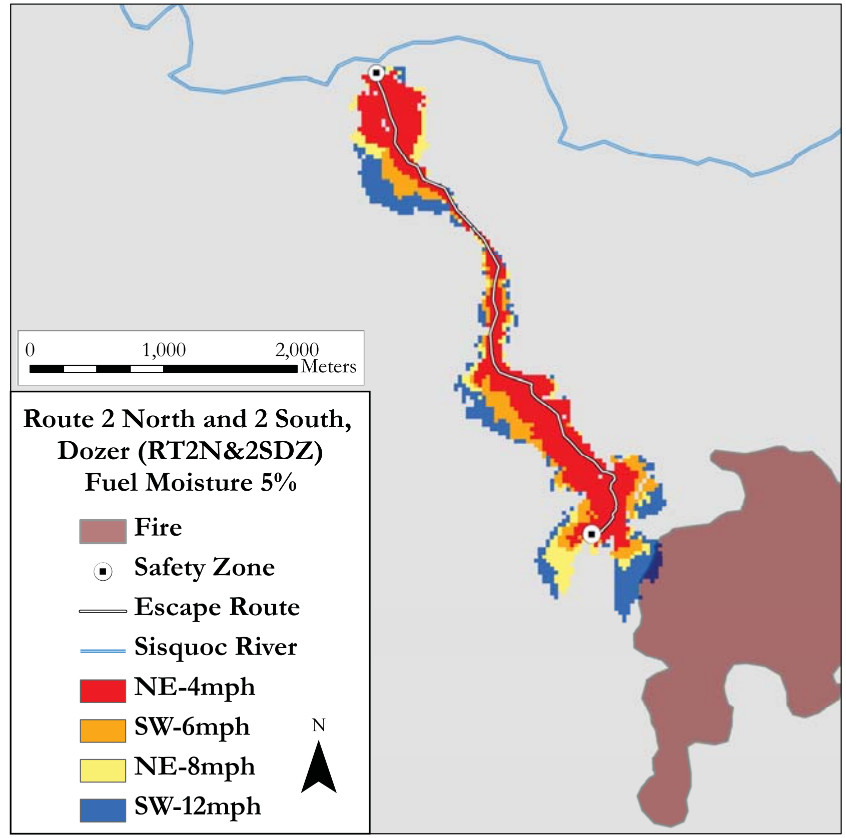


Figure 4.4: Trigger Buffers for R2NDZ & R2SDZ at Fuel Moisture 5% and 8%

R3FT

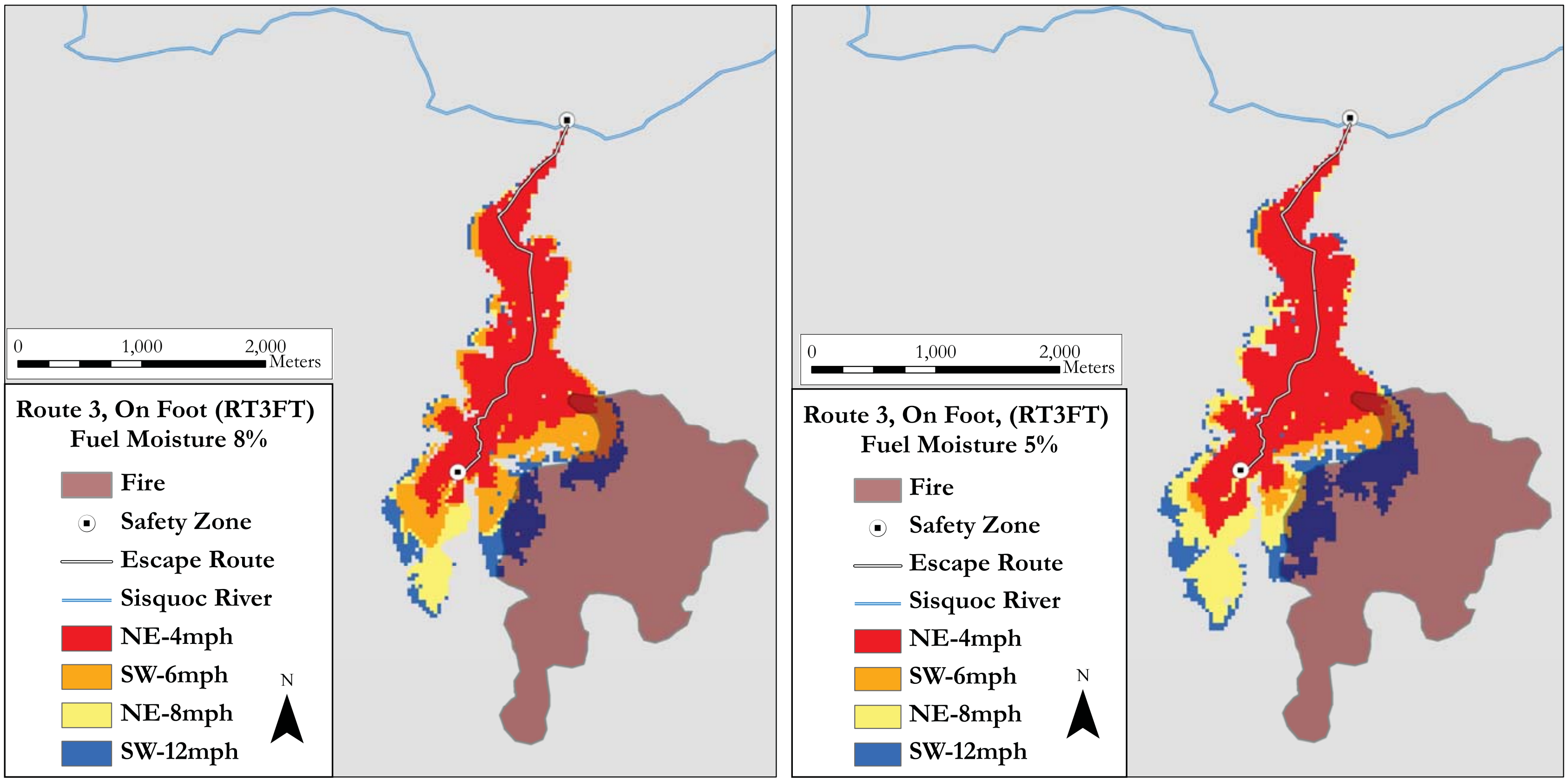


Figure 4.5: Trigger Buffers for R3FT at Fuel Moisture 5% and 8%

R3DZ

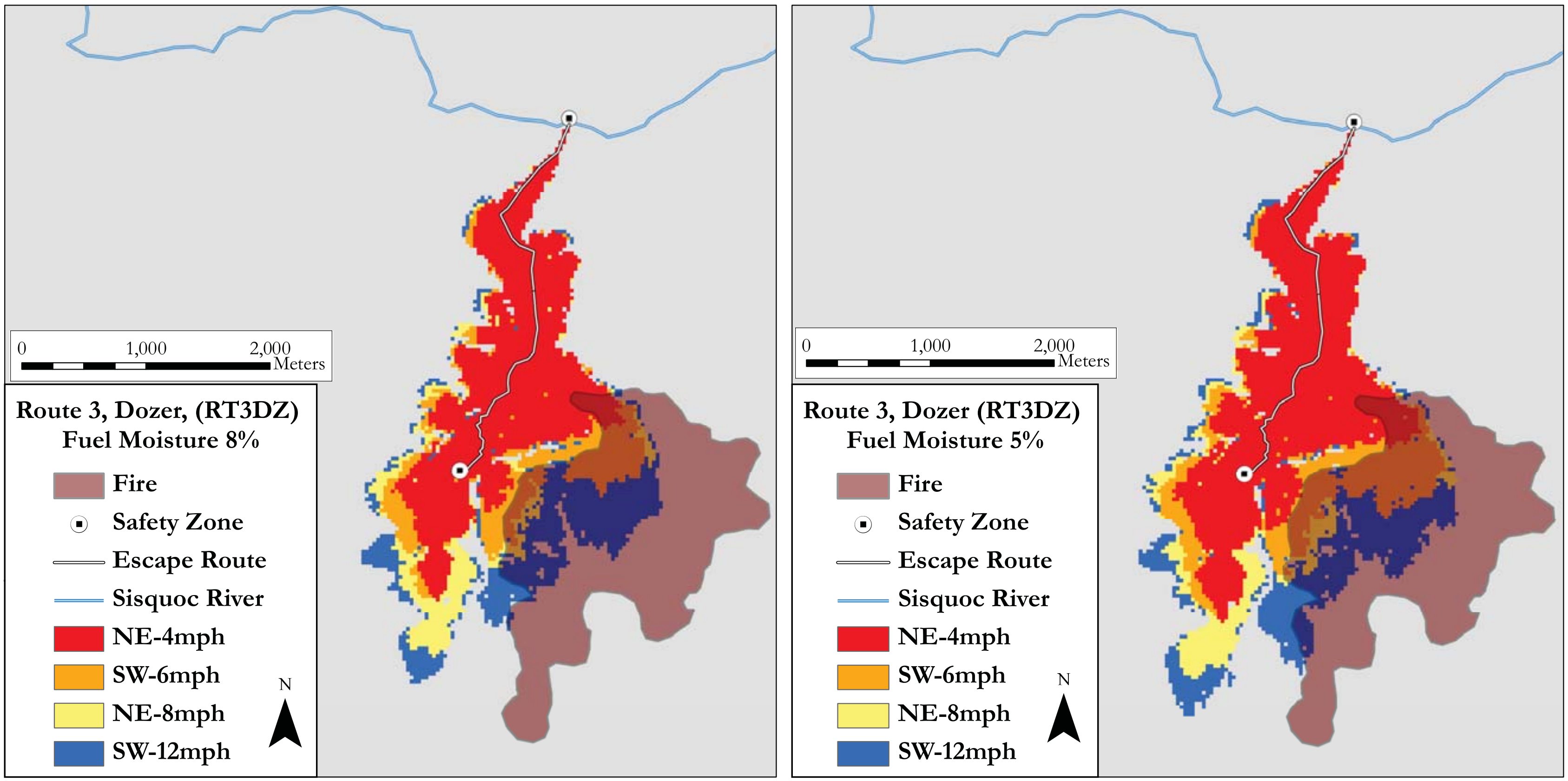


Figure 4.6: Trigger Buffers for R3DZ at Fuel Moisture 5% and 8%

R4FT

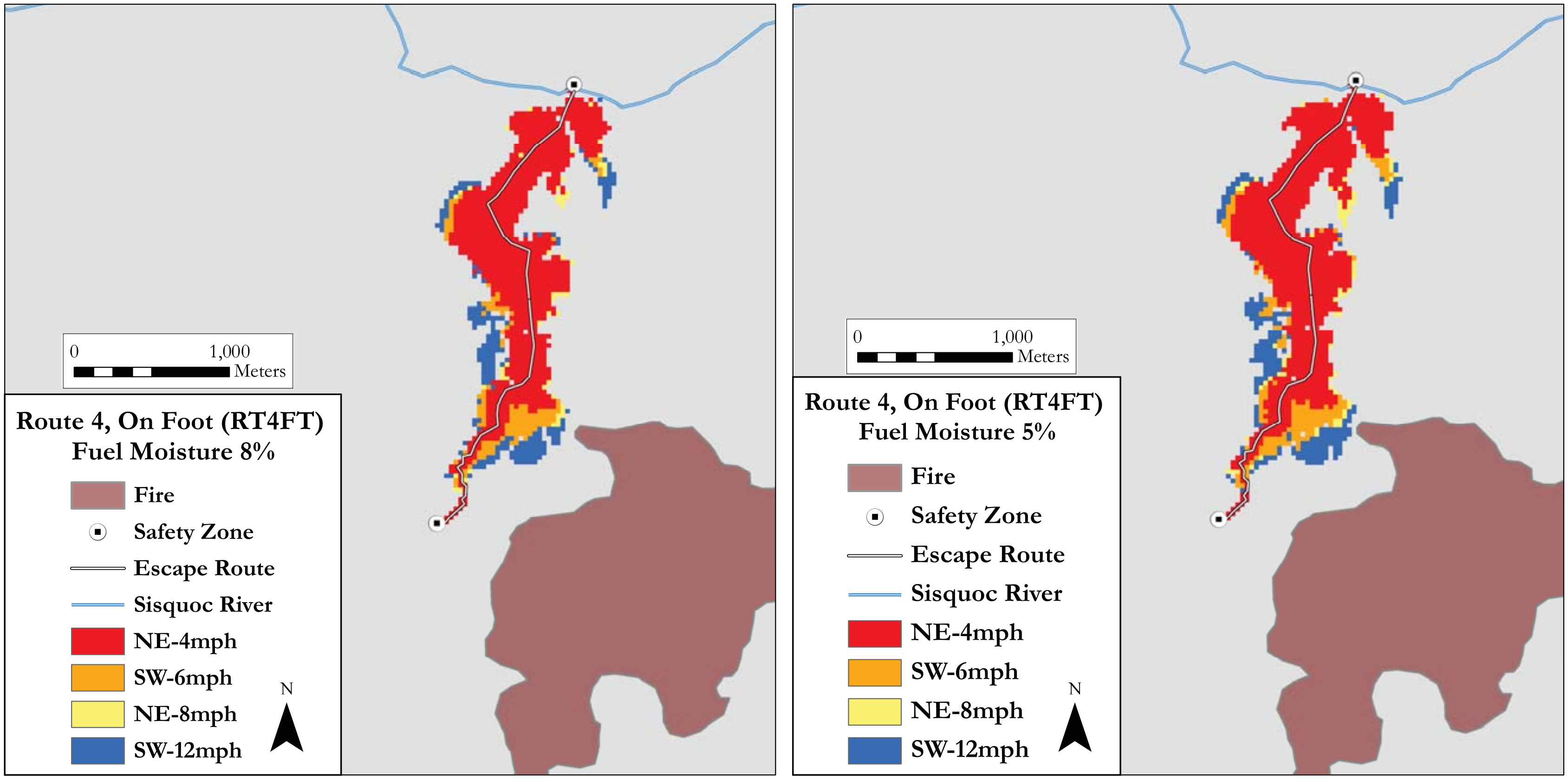


Figure 4.7: Trigger Buffers for R4FT at Fuel Moisture 5% and 8%

R4DZ

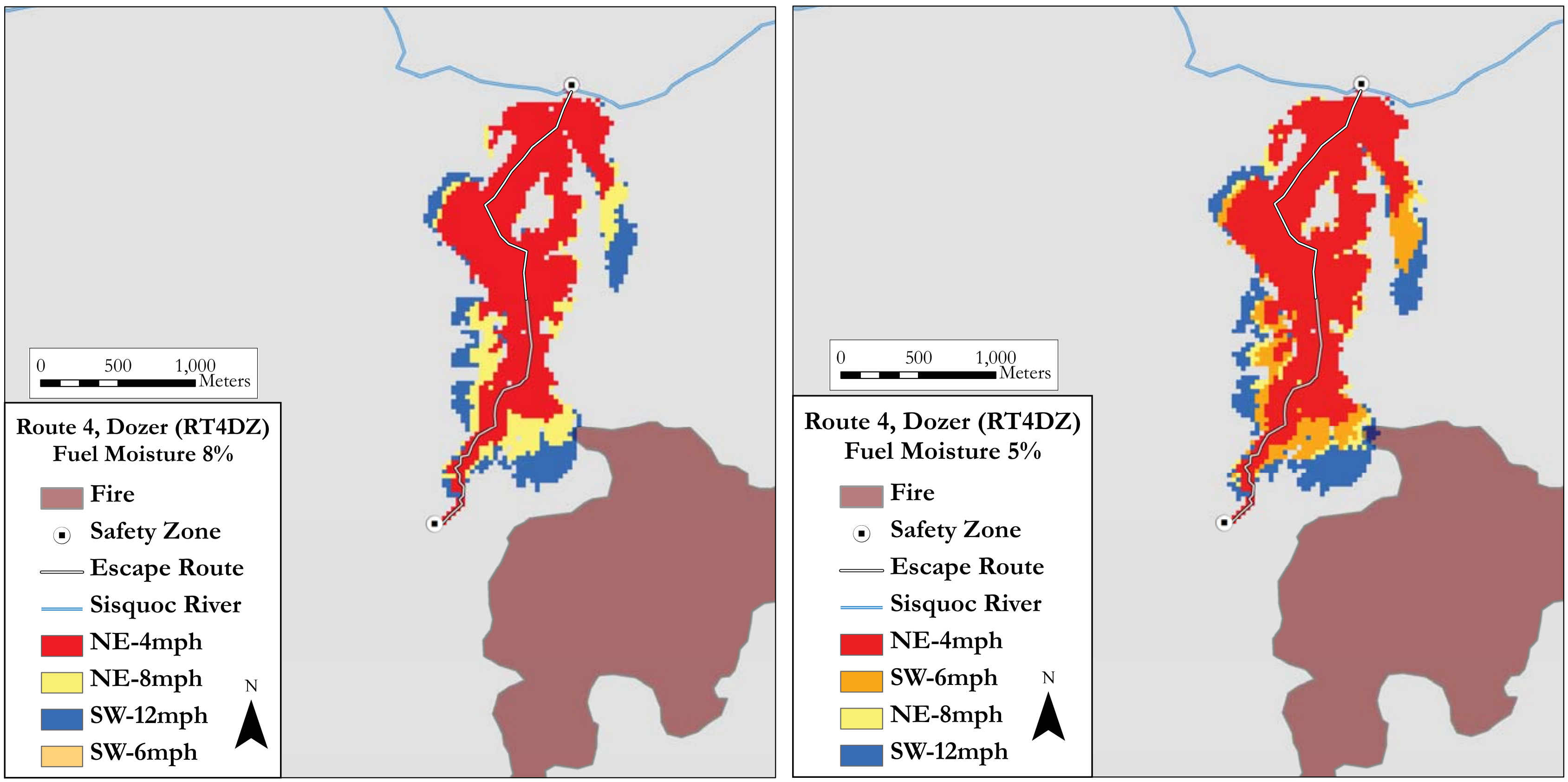


Figure 4.8: Trigger Buffers for R4DZ at Fuel Moisture 5% and 8%

A visual comparison between Figure 4.1 and Figure 4.2 best demonstrates the effect travel time has on the output trigger's buffers. The outputs for R1FT (Figure 4.1) are all distinctly larger buffers than those of R1EN (Figure 4.2). Travel on foot was much slower than traveling in an engine; thus, the buffer needed to be large enough to adjust for this time difference. R1EN's buffers are smaller and tight to the road, giving the resource greater time to complete the tactical objective safely than on foot traffic would have. We can also observe the majority of the trigger buffer on the south side of the road, which indicates fuel characteristics and wind direction make fire spread from that direction more of a threat. The trigger buffer difference between on foot travel and engine travel was the most noticeable, but when we compared on foot travel to dozer travel in all the other scenarios, there was less of a dramatic change in size and shape due to the travel times being closer together.

A longer travel time results in an increase in size and shape of a trigger buffer. The relationship was evident in a comparison between R2S (Figures 4.3 and 4.4) and R3 (Figures 4.5 and 4.6) for both DZ and FT travel. The travel times were approximately 40% to 50% less for R2S than for R3. Hence, when R3's network and subsequent trigger buffer was computed, fuel and terrain inputs to the south, which were conducive to increasing fire spread rate, were incorporated into the model. The result was a substantially larger trigger buffer area to the south for R3, as well as a sizable difference in max edge distance measurements between the two routes, and all R3's trigger buffers are overlapping the fire.

One distinctive feature of R4's trigger buffers was the peninsula like feature on the northeastern part of the buffers (Figure 4.7 and 4.8). This distinct shape also occurred in the southern portion R2N and R2S output buffers (Figure 4.3 and 4.4) and more predominately in R3 (Figure 4.5 and 4.6). This phenomenon was a result of the model adjusting for terrain and vegetative features that are in alignment for rapid-fire spread. Fire tends to burn faster up hill; the steeper the slope the faster fire travels, due to conductive and radiant processes of a flame front, which ultimately preheats the fuel bed in front of the fire making the vegetation more receptive to burning. Hence, this feature of the trigger buffer was located on slopes with a receptive fuel bed for faster fire spread adjacent to ridges where fire runs are more intense, which indicates correct allocation of a buffer's area by the model.

In all 10 tactical scenarios, weather and fuel condition FM8 – NE – 4 mph produced the least total area, whereas FM5 – SW – 12 mph had the largest area, resulting in an average of 52% (+/- 7%) increase in total area as the conditions for fire spread increased. This increase was attributed more to wind speed than any other factor. Fuel type and location, which as mentioned above does have an affect on area (albeit minimal in most cases), plays a stronger role in affecting a trigger buffer's shape. This occurrence is best expressed in a comparison between R2NFT and R2NDZ in Figures 4.3 and 4.4; each mode had a different travel time, but each had the same approximate total area as well as trigger buffer output shape. This can be attributed to the Sisquoc River that is located north of the route, which acts as a large barrier for the fire spread model.

The Sisquoc River's location also blunted the increase in trigger buffer area and shape for all of R4's scenarios. Travel time for both R4 and R3 were very close, and their location is exactly the same, yet when we compare Figures 4.7 and 4.8 to Figure 4.5 and 4.6, their trigger buffers are considerably different. Even though the buffer's total area should be allocated differently over the terrain, due to the travel time difference at each end of both routes, we might expect their total area to be closer in measurement. However, this was not the case, as fire spread would be halted significantly at the river.

We were also able to observe from the outputs what containment lines, and conditions associated with them, will likely be compromised before tactics are even implemented. As shown in Figure 4.5 and 4.6, based on the evacuation time, all R3's trigger buffers for each travel mode are overlapped with the fire's edge. Given this result, which is examined in greater depth below, implementing Containment Line A with R3 as an escape route would put resources in harm's way before construction on the line was completed, and therefore it would not have a high success rate for constructing an indirect handline. Time and resources would subsequently be best allocated elsewhere. This would also be a consideration with trigger buffers R1FTFM5-SW12 mph, R1FTFM8-SW12 mph, R2SDZFM5-12 mph, R2SDZFM8-12 mph, R4DZFM8-SW12 mph, and R4DZFM5-NE8 mph and SW12 mph. In comparison, all trigger buffer outputs for R1EN, R2NFT, R4FT and R2NDZ had no contact whatsoever with the fire. This is mainly due to their location and travel times, which ultimately may influence margin of safety considerations for that July 5th's planned tactics.

Travel time and wind speed had the greatest impact on trigger buffer distance from the protected resource. For instance, the mean distance and the maximum mean distance for the range of trigger buffers for R3DZ, which had the slowest travel time of 175 min, was 528 m and 1486 m. Conversely, R1EN, which had the fastest travel time of 20 min, had a mean distance of 32 m and a maximum mean distance of 128 m. Even though there was a wide range in ten tactical trigger buffer distances, this was the relationship between travel time and trigger buffer distance we expected to observe. As travel time increases, we inferred that the trigger buffer edge distance needed to activate a well-timed decision would need to increase proportionally.

While there was quite a large variation in the mean and mean max distance from protected resource to trigger buffer edge across the 10 tactical scenarios, the difference of the mean distance to mean max distance across the ten tactical scenarios was significantly less dramatic. By observing a ratio of the mean and the max mean trigger buffer distances for each of the tactical situations, we observed a strong correlation between the growth of trigger buffer distances as the range of input conditions increases throughout the range of travel modes and times. The ratio of the mean/mean max for all ten scenarios was .338 (+/- .033). The ratio was even stronger when travel modes are aggregated by travel mode. For on foot travel, the ratio was .343 (+/- .009), and for dozer travel it was .354 (=/- .009). From these results, given a range of conditional inputs, we can assume strong continuity between the range in the total area and distance of trigger buffer outputs, as the transportation modes and times are changed.

Both wind direction and speed, as well as vegetation location and type, influenced the direction and distance of the 80 trigger buffers. As illustrated in Figure 4.9, even though Containment lines A and B run mainly north to south and Containment Line C runs northwest to southeast, the maximum extents for the trigger buffers run in a southwest to northeast direction, which was to be expected. The trigger buffers would need to be extended in the direction of oncoming winds, which affect fire's spread, in order to establish enough time for resource evacuation. Although there was a northeast to southwest trajectory of max extent, all eight trigger buffers for each of the 10 tactical scenarios are mostly grouped together rather than split in half due to the two different wind directions. Additionally, most groups extended toward the southwest. We concluded that this was most likely due to terrain and fuels creating stronger fire behavior outputs in the southwest direction, and thus pulling the direction of the trigger buffers in that direction. Subsequently, as time increases across the ten tactical scenarios, the resulting trigger buffers all needed to extend more in the southwest direction.

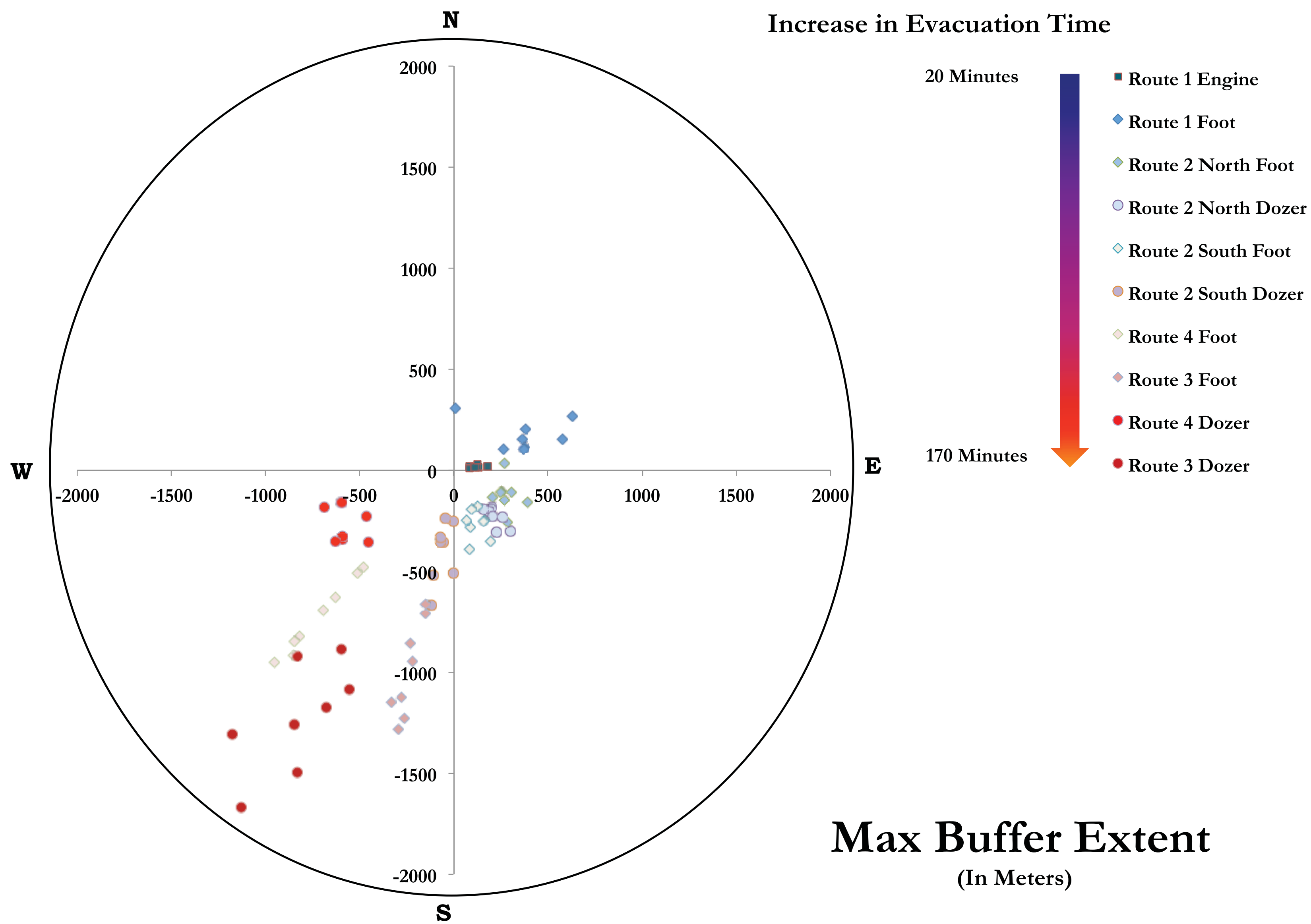


Figure 4.9: Direction and Distance of the Max Extent for all 80-Trigger Buffers.

5 DISCUSSION

Tactical decision-making in highly stressful and time sensitive situations is extremely challenging and can often be problematic, potentially leading to unsuccessful or incorrect results (United States Fire Administration 2002). The wildland fire environment is an incubator of such stressful scenarios and risk is inherent in many tasks conducted by wildland firefighters. Analytical processes have the ability to aid in what is most often an intuitive decision process conducted in tumultuous situations by firefighters with a wide range of experience, knowledge, and capabilities. A firefighter's intuition can be altered or compromised by human factors such as insufficient knowledge of surroundings and conditions, inexperience, overextension of resources, or loss of situational awareness. Uncertainty and limitations associated with GIS and fire behavior models are well documented (Alexander 2004; Zhang & Goodchild 2002), and decisions based solely on model outputs are unwarrantable in most tactical situations involving fire suppression. For example, problems would arise if the trigger buffer size needed for evacuation fell beneath the cell resolution size(in this case 30 m), or the fuel and weather conditions were outside the range of the predicted conditions. However, these types of errors can be overcome by conservative interpretation of predicted conditions paired with accurate-as-possible model outputs.

What we demonstrate here is an area where both analytical and intuitive decision-making processes can be coupled together to make effective, efficient, and more advantageous decisions. This process has the possibility to ensure more accurate decisions, with the firefighter's safety as the highest priority. For the purpose of this study, we constructed scenarios based on resource availability, in addition to weather and fuel conditions predicted for Division C on the Zaca Fire for July 5th. Fuel and terrain models were also retrieved from LANDFIRE for our study area. We developed a methodology for how to calculate a travel time for different firefighting resources, which adjusts for changes in slope, utilizing a modified Tobler's Hiking Function. To determine uncertainty, these methods worked well for consistency and keeping the scenario realistic as possible, but if the WUIVAC model were to be used in future tactical situations, planning combat and modeling adjustments for containment lines, escape route travel times, designated safety zones, and resource capabilities would theoretically be determined and assessed by fire managers on the ground and communicated to the person running the model. Since weather conditions are dynamic, real time weather observations taken on site at designated intervals could also be communicated, and models would be updated to match current conditions, ultimately decreasing uncertainty. We only tested for a range of expected conditions for that day, so we are unable to address the characteristics of the trigger buffers that might occur under more extreme conditions. For example high wind gusts above the predicted wind speeds, which would affect the output buffer, were not accounted for in the model. Having regularly updated weather observations, as well as having conservative estimates of travel times and weather and fuel conditional predictions would possibly help regulate this uncertainty.

Based on the trigger buffers resulting from the 80 scenarios, WUIVAC was able to show usefulness in tactical decision-making. We were able to observe how the range of fire behavior conditions for that day impacted the resulting trigger buffers and the variability associated with them. This allowed us to account for, and subsequently plan for and assess, the potential dynamic changes in wind, fuel moisture, etc. for a whole operational period. A trigger buffer's size and shape varied strongly between the 10 routes, due to differences in travel time. However, adjusting for travel time, the variation between the high and low weather and fuel conditional inputs across the ten scenarios was minimal, which indicates stronger model output consistency.

As mentioned above, travel time is influential in dictating trigger buffer total area and shape by allowing the model to take into consideration more terrain and fuel characteristics, which may or may not have properties that allow for more rapid fire spread. The WUIVAC model creates a network based on minimal fire spread time for each 30 m cell in our study area, which it then uses to create a buffer based on the designated evacuation time. The larger the evacuation time needed, the larger the buffer size and edge distance needs to be. As the buffer's edge moves farther out from the protected resource (i.e., containment line) due to time needed to evacuate, the more fuel and terrain characteristics the model is able to consider. These characteristics may or may not be conducive to increased fire spread, and our resulting buffers highlight this relationship (see Figure 4.9). Understanding this relationship may also help a firefighting resource in assigning a trigger buffer edge to a real world feature (e.g., ridge, river, road) for purposes of a trigger point. Adjustments by the fire manager or resource can be made to the trigger point to accommodate their understanding, or lack of understanding, of the fire dynamics connected to an area. Conservative or aggressive trigger points could be determined, in which the model gives a reference point with which to start. This conceptual point of reference would aid in the understanding of pre-identified evacuation thresholds, or other tactical plans, for a range of experience from the novice firefighter to most seasoned, and this link of understanding, or discussion point, between the two would serve as a possible framework for better communication.

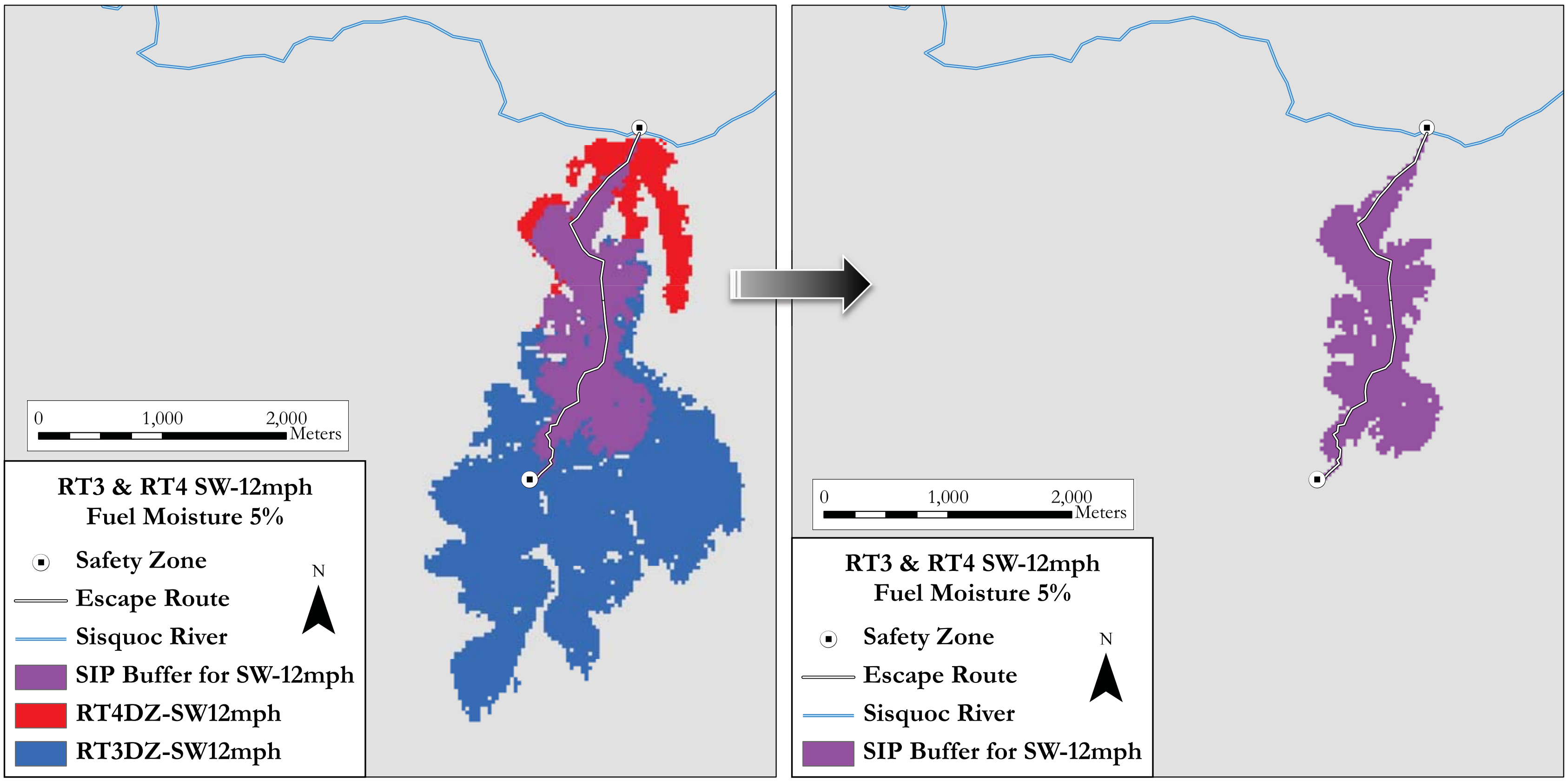
As shown in Figures 4.5 and 4.6, based on the evacuation time, all R3's trigger buffers for each travel mode are overlapped with the fire's edge. Given this result, implementing Containment Line A with R3 as an escape route has an extremely small if not nonexistent margin of safety, and would put resources in harm's way before construction on the line was completed, and therefore it would not have a high success rate for indirect handline. Time and resources should subsequently be allocated elsewhere. Once again, a consideration with trigger buffers R1FTFM5-SW12 mph, R1FTFM8-SW12 mph, R2SDZFM5-12 mph, R2SDZFM8-12 mph, R4DZFM8-SW12 mph, and R4DZFM5-NE8 mph and SW12 mph is also warranted. These Containment Lines would still be viable for indirect tactics, although tactical change would need to be implemented, or at the very least considered, when wind speeds increased. Efficiency in decision-making can be improved when tactics are analyzed in advance, given all relevant input (i.e., handline location, travel time for resources, weather and fuel conditions). If a resource is using weather thresholds (i.e., wind speed increase or direction change) for their trigger point, the WUIVAC output trigger buffer could aid in determining what that threshold might be. Also, for the purposes of indirect attack, we were able to see clearly which containment lines and resource allocations would have a more successful outcome for that day. This also demonstrates WUIVAC's ability to increase efficiency when decisions involving firefighter resource allocation, fuel management, and other cost factors of the fire are made.

5.1 Shelter-In-Place Trigger Buffer

An additional concept we discovered in this process was the idea of a shelter-in-place (SIP) trigger buffer, which is illustrated in Figure 5.1. When we overlay a conditional buffer (e.g. FM5-SW12 mph) of R4 with the same conditional trigger buffer of R3, the intersection of the two is an area where both the northern and southern safety zones are unattainable by the fire resource, and the best option for the escaping fire fighter is to SIP. Just like the trigger point buffer, this "shelter buffer" could be used to assign a geographical feature, where if the fire spread breaches the edge, then a predetermined decision is made.

The potential for this concept in tactical decision-making is two fold. First, the fire resource could use time that would normally be dedicated to traveling the remaining distance of the escape route, which in theory would end poorly, to pick the best immediate shelter and prep before the burnover occurs (e.g., remove vegetation, set a backfire), providing greater potential for survival. This trigger would be communicated and understood prior to the suppression tactic being implemented, and it should be part of that resource's situational awareness. When stress associated with an approaching fire front, rapid evacuation, and fatigue were present, the point of no return would be predetermined and not decided on-the-fly under hectic conditions. Second, when planning the suppression tactics for an operational period, a fire manager could further assess risk and the margin of safety associated with a proposed tactic. A greater ratio between an evacuation trigger buffer and the SIP trigger buffer would indicate a higher success rate.

R3DZ & R4DZ



Example of a Shelter-In-Place (SIP) Trigger Buffer, which in this Example is an Overlay of R3 and R4 at FM5% and Winds SW-12 mph

6 CONCLUSION

Eighty scenarios, which span a range of tactics and predicted fire behavior conditions for the July 5th operational period, were derived in order to analyze the uncertainty associated with output trigger buffers. A qualitative and quantitative analysis provides a clear depiction of how containment line location, fire behavior conditional inputs (e.g., fuel moisture, wind inputs, terrain) and evacuation time control the size, shape, and direction of a trigger buffer. Travel time was the most important factor in determining trigger buffer area and extent for the 80 scenarios. Unlike wind and fuel moisture, travel time and distance to safety zone can be predicted with greater certainty. Overall, uncertainty linked to our output trigger buffers was minimal under the tested ranges of conditions, allowing for a firefighter resource to use them as a reference in planning indirect tactical objectives. More specifically, the WUIVAC model preformed as we anticipated. According to our research, uncertainty associated with the range of inputs would have little hindrance in developing trigger points based on a geographical location. Furthermore, the margin of safety was measurable, as demonstrated in our results, which has the potential to aid decision-making by assessing and determining risk thresholds.

Nevertheless, additional research is needed to assess the use of WUIVAC in different fuel and terrain types along with applying the model to different tactical scenarios. Further analysis should also include determining the uncertainty associated with buffers generated from observed conditions in intervals throughout the day (i.e., every hour). As model processing times increase, a more real-time model could be used in fire operations at the divisional level, where the Division Officer would be able to get on-the-spot trigger buffer outputs, and allow for more informed decision-making.

REFERENCES

Alexander, M., & Thomas, D. (2004). Forecasting wildland fire behavior: aids, guides, and knowledge-based protocols. *Fire Management Today,* 64 (1), 4-11.

Anguelova, Z., Stow, A., Kaiser, J., Dennison, P., & Cova, T. (2010). Integrating fire behavior and trafficability models to assess fire danger to pedestrians within the US/Mexico border zone. *The Professional Geographer*, 62 (1), 230-247.

Baxter, G., Alexander, M., & Dakin, G. (2004). *Travel rates by Alberta wildland firefighters using escape routes on a moderately steep slope.* FERIC Advantage Report, 5 (25), 15 pp.

Beighley, M. (2004). Beyond the safety zone: creating a margin of safety. *Fire Management Today,* 64 (1), 78-81.

Butler, B., & Cohen, J. (1998). Firefighter safety zones: a theoretical model based on radiative heating. *International Journal of Wildland Fire,* 8 (2), 73-77.

Butler, B., & Cohen, J. (2004). Firefighter safety zones: how big is big enough? *Fire Management Today*. 64 (1), 82-85.

Butler, B.W., Cohen, J.D., Putnam, T., Bartlette, R.A., & Bradshaw, L.S. (2000). *A method for evaluating the effectiveness of firefighter escape routes.* In: Butler, B.W.; Shannon, K. (Eds.), Proceedings of the 2000 International Wildfire Safety Summit, International Association Wildland Fire, Montana City, MT, 42-53.

Cal-Fire. (2007). Zaca fire incident information. Retrieved October 27, 2010, from http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=190.

Cheney, N., Gould, J., & McCaw, L. (2001). The Dead-Man-Zone: a neglected area of firefighter safety. *Australian Forestry,* 64 (1), 45-50.

Cook, J. (2004). Trends in wildland fire fatalities. USDA Forest Service National Fire Operations Safety Information Briefing Paper. National Interagency Fire Center. Retrieved October 30, 2010, from http://www.wildfirelessons.net/Additional.aspx?Page=84..

Cook, R. (2003). Show low Arizona inferno: evacuation lessons learned in the Rodeo-Chedeski fire. *National Fire Protection Association Journal*, 10–14.

Close, K. (2005). *Fire behavior vs. human behavior: why the lessons from Cramer matter*. Paper presented at the Eighth International Wildland Fir e Safety Summit, Missoula, MT. Retrieved December 29, 2010, from http://www.wildfirelessons.net/documents/Close.pdf

Cova, T., Dennison, P., Kim, T., & Moritz, M. (2005). Setting wildfire evacuation trigger-points using fire spread modeling and GIS. *Transactions in GIS,* 9 (4), 603-617.

Cova, T., Drews, F., Siebeneck, L., & Musters, A. (2009). Protective actions in wildfires: evacuate or shelter-in-place? *Natural Hazards Review*, 10 (4), 151-162.

Dakin, G. (2002). Ground rates of travel by fire crews using escape routes: an interim report. *FERIC Advantage Report*, 3 (15). 7 pp.

Dennison, P., Cova, T., & Moritz, M. (2007). WUIVAC: a wildland-urban-interface evacuation trigger model applied in strategic wildfire scenarios. *Natural Hazards*, 41, 181-199.

Dennison, P., Moritz, M., & Taylor, R. (2008). Examining predictive models of chemise critical live fuel moisture in the Santa Monica Mountains, California. *International Journal of Wildland Fire*, 17, 18-27.

Finney, M. (2004). *FARSITE: fire area simulator-model development and evaluation.* Res. Pap. RMRS-RP-4, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M. (2006). *An overview of FlamMap fire modeling capabilities.* Fuels management - How to Measure Success: Conference Proceedings. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213-220.

Forthofer, J., Shannon, K., & Butler, B. (2009). *Simulating diurnally driven slope winds with WindNinja.* In: Proceedings of 8th Symposium on Fire and Forest Meteorological Society; October 2009, Kalispell, MT, 13-15.

Gleason, P. (2004). L.C.E.S. A key to safety in the wildland fire environment. *Fire Management Today*, 64 (1), 70-71.

Greenlee, J., & Greenlee, D. (2003). Trigger points and the rules of disengagement. *Fire Management Today*, 63 (1), 10–13.

Halsey, R. (2006). Weather, fuels, and suppression during the 2003 cedar fire: which variables made the critical difference? *Proceedings, 3rd International Fire Ecology and Management Conference.* San Diego, CA: Association for Fire Ecology.

Keeley, J., Fotheringham, C., & Morais, M. (1999). Reexamining fire suppression impacts on brushland fire regimes. *Science*, 284, 1829–1832.

Keeley, J., Safford, H., Fotheringham,C., Franklin, J. & Moritz, M. (2009). The 2007 Southern California wildfires: lessons in complexity. *Journal of Forestry,* 107, 287-296.

Putnam, T. (1995). *Findings From the Wildland Firefighters Human Factors Workshop – Improving Wildland Firefighter Performance Under Stressful, Risky Conditions: Towards Better Decisions on the Fireline and More Resilient Organizations.* USDA Forest Service, Missoula Technology and Development Center Technical Report 9551- 2855-MTDC. Missoula, MT. 76 pp.

LANDFIRE (2010). Data is available at: http://www.landfire.gov/products_tools.php

Mangan, R. (2001). *Investigating wildland fire entrapments*. Tech Report 0151-2823-MTDC. Missoula, MT. USDA – Forest Service, Missoula Technology & Development Center. 34 pp.

Mangan, R. (2007). *Wildland firefighter fatalities in the United States: 1990–2006*. NWCG PMS 841. Boise, ID: National Wildfire Coordinating Group, Safety and Health Working Team, National Interagency Fire Center. 28 pp.

McKelvey K., & Busse K. (1996). *Twentieth century fire patterns on forest service lands.* Sierra Nevada Ecosystems Project: Final Report to Congress. Davis, CA: University of California, 1119–38.

McDaniel, J. (2007). The Zaca Fire: bridging fire science and management. *Wildfire lessons learned Center.* Retrieved October 30, 2010, from http://www.wildfirelessons.net/Additional.aspx?Page=110.

Moritz, M., Morais, M., Summerell, L., Carlson, J., & Doyle, J. (2005). Wildfires, complexity, and highly optimized tolerance. *Proceedings of the National Academy of Sciences USA*, 102, 17912-17917.

McLennan, J., Holgate, A., Omodei, M., & Wearing, A. (2006). Decision making effectiveness in wildfire incident management teams. *Journal of Contingencies and Crisis Management,* 14 (1), 27-37.

Munson, S. (2000). *Wildland firefighter entrapments: 1976-1999.* Tech. Rep. 0051- 2853-MTDC. Missoula, MT: United States Department of Agriculture Forest Service, Missoula Technology and Development Center.

National Interagency Fire Center (NIFC) (2010). Historical wildland fire fatality statistics. Retrieved October 21, 2010, from http://www.nifc.gov/safety/reports/year.pdf.

NWCG Joint Task Force (1980). Report of the task force on study of fatal and near fatal wildland fire accidents. Retrieved October 30, 2010, from http://www.wildfirelessons.net on.

Pyne, S., Andrews, P., & Laven, D. (1996). *Introduction to Wildland Fire, 2 Ed.* New York: Wiley.

Pyne, S. J. (2001). *Year of the fires: The Story of the Great Fires of 1910*, New York: Viking.

Spencer, B. G. (1958). *The Big Blowup: The Northwest's Great Fire*, Caldwell, ID: Caxton Printers, Ltd.

Stephens S. (2005). Forest fire causes and extent on United States Forest Service lands. *International Journal of Wildland Fire,* 14, 213-22.

Reeves, C., Ryan, C., Rollins, G., & Thompson, G. (2009). Spatial fuel data products of the LANDFIRE project. *International Journal of Wildland Fire,* 18, 250-267.

Rollins, M. (2009). LANDFIRE: A nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire*. 18, 235-249.

Ruby B., Leadbetter III, G., Armstrong, D., & Gaskill, S. (2003). Wildland firefighter load carriage: effects on transit time and physiological responses during simulated escape to safety zone. *International Journal of Wildland Fire,* 12, 111-116.

Russo, E., Schoemaker, P. (1989). *Decision traps.* New York: Doubleday/Currency.

Taynor, J., Klein, G., & Thordsen M., (1987). *Distributed decision making in wildland firefighting.* (KATR-858[A]-04F). Yellow Springs, OH: Klein Associates, Inc. Prepared under contract MDA903-85-C-0327 for the U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA.

Tobler, W. (1993). *Three presentations on geographical analysis and modeling: 1) non-isotropic modeling, 2) speculations on the geometry of geography, 3) global spatial analysis.* Technical Report 93-1. 24 p. Retrieved March 11, 2010, from http://www.ncgia.ucsb.edu/Publications/Tech_Reports/93/93-1.PDF.

United States Fire Administration, National Fire Protection Association (2002). *A needs assessment of the U.S. fire service: a cooperative study authorized by U.S. Public Law 106-398.* Washington D.C.: FEMA, U.S. Fire Administration, NFPA International.

USDA Forest Service (1957). *Report of the task force to recommend action to reduce chances of men being killed by burning while fighting fire.* Retrieved October 27, 2010, from http://www.wildfirelessons.net/documents/Report_of_Fire_Task_Force_1957.pdf.

USDA Forest Service (1967). *Report of the fire safety review team: a plan to further reduce chances of men being killed by burning while fighting fire.* USDA Forest Service. Retrieved October 27, 2010, from http://www.fireleadership.gov/toolbox/staffride/downloads/lsr1/lsr1_fire_safety_team.pdf.

Wilson, Carl C. (1977). Fatal and near-fatal forest fires: the common denominators. *The International Fire Chief*, 43 (9), 9-15.

Weick, K. (1993). The collapse of sensemaking in organizations: the Mann Gulch disaster. *Administrative Science Quarterly*, 38, 628-652.

Weick, K., Sutcliffe, K. (2001). *Managing the Unexpected*. San Francisco: Jossey-Bass.

Westerling, A. L., Hidalgo H., Cayan, D.R., & Swetnam, T. (2006). Warming and earlier spring increases western us forest wildfire activity. *Science*, 313, 940-943.