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Data Fusion for Decision Support

Rebecca A. Unruh

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**DATA FUSION
FOR
DECISION SUPPORT**

THESIS

Rebecca A. Unruh, Captain, USAF

AFIT-ENY-14-M-48

**DEPARTMENT OF THE AIR FORCE
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AFIT-ENY-14-M-48

DATA FUSION FOR DEISION SUPPORT

THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Astronautical Engineering

Rebecca A. Unruh, BS

Captain, USAF

March 2014

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DATA FUSION FOR DEISION SUPPORT

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Abstract

This thesis demonstrates the utility of fusing data from multiple sources, including remote sensing data, in a Geographic Information System (GIS) for decision support by designing a new method of assessing wildfire risk in the wilderness urban interface (WUI) to facilitate better informed land management decisions and reduce mission impacts of wildfires on the military. Information from remote sensing systems has been used for decades to support decisions. Today, data are time and location tagged, making it possible to correlate and fuse disparate sources in a GIS, from which data can be stored, analyzed, and the resulting information shared. The GIS, relating data based on spatial attributes, has become an ideal fusion platform and decision support tool. In demonstration, decades of work in fire science were put to work, applying the Fire Susceptibility Index (FSI) on a new, 30 m scale with Landsat 8 data. Eight data sources were fused in a GIS to identify high-risk patches of wildland by calculating the FSI and preparing it for meaningful analysis and sharing. The initial results, qualitatively validated with wildfire behavior basics, appear promising, providing a view of fire danger in the landscape not seen in the current state of practice.

Keywords: Air Force, Data Fusion, Decision Support, Emergency Management, Fire Susceptibility Index, Geographic Information Systems, Landsat 8, Remote Sensing, Wildfire, Wildland Urban Interface

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Rebecca A. Unruh

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DATA FUSION FOR DECISION SUPPORT

I. Introduction

The military uses remote sensing to gather information upon which decisions are made, both those made by humans and those coded into hardware and software logic. Many military remote sensor systems were originally designed to collect specific information on a narrow set of requirements. The data streams from disparate programs often remained isolated from one another from processing to information output. Over the last several decades, the use of the data from individual sources has expanded, but by no means has it seen the wide and varied use seen with civil platforms such as the Landsat missions or the Geostationary Operational Environmental Satellites (GOES). During the same intervening time, Geographic Information Systems (GIS) have developed and become powerful platforms for data fusion. A GIS gives users the ability to collect, store, analyze, and share spatial data and information. The GIS user base is broad, from science and engineering studies to outlining business strategies and urban development. This broad user base can offer the military many different perspectives when it comes to managing information and tackling problems.

Problem Statement

In this thesis I will demonstrate the utility of fusing data from multiple sources, including remote sensing data, in a GIS to facilitate decision making.

To accomplish this, the effort will focus on addressing an often overlooked problem for the military: wildfire. Building from decades of work in fire science and emergency management, I present a method to assist in assessing wildfire risk at Air Force (AF) bases in the wildland urban interface (WUI) to facilitate better informed land management decisions.

Background and Understanding the Problem

The field of remote sensing is quite vast and geographic information systems are employed to solve an even broader set of problems. Wildfire in the WUI was chosen as an arena to demonstrate the utility of working with remote sensing data in a GIS and narrow the focus on a defined problem for the AF and Department of Defense (DoD). This section takes an introductory look at the problem and outlines Chapter 2 content.

The International Society for Photogrammetry and Remote Sensing (ISPRS) defines remote sensing as “the art, science, and technology of obtaining reliable information from non-contact imaging and other sensor systems about...physical objects and processes through recording, measuring, analysing, and representation” (1:3). Remote sensing data are, by nature, spatial, spectral, and temporal. The design of remote sensing systems limit how much data we can collect spatially, spectrally, and temporally, as will be seen in Chapter 2. One way to overcome this is through data fusion.

In *A Review of Data Fusion Techniques*, Federico Castanedo relays the “most accepted definition of data fusion...: ‘A multi-level process dealing with the association, correlation, [and] combination of data and information from single and multiple sources

to achieve refined position, identify estimates, and complete and timely assessments of situations, threats, and their significance” (2:1). Data fusion itself is a large application area. In Chapter 2, a classification framework for understanding data fusion is presented along with a discussion of where this demonstration fits into that classification.

One platform particularly suited to data fusion is the GIS. GIS “are a special class of information systems that keep track not only of events, activities, and things, but also of where these events, activities, and things happen or exist” (3:4). The spatial nature of remote sensing data makes a GIS an ideal platform for exploring, analyzing storing, and sharing the data. GIS basics are introduced in Chapter 2, focusing on topics of interest for working with remote sensing data, data fusion, and sharing information.

The AF, and the DoD as a whole, manages significant tracts of wildland. Our ability or inability to manage the wildland with respect to wildfire activity and the WUI will impact how we execute the AF mission, from training to operations. As budgets continue to tighten, decision makers have less room for surprises or errors in wildland management. A new decision support tool can help leadership decide where to apply resources, particularly with the alarming trends seen with wildfires in the past few years.

Wildfire science is a large topic area. In Chapter 2, wildfire is introduced along with its vocabulary and behavior. Then the focus shifts to the current practice of fire danger rating and the data that feeds the National Fire Danger Rating System (NFDRS). Understanding the limits of NFDRS, a few of the remote sensing algorithms used to assess wildfire risk are explored, including the Fire Susceptibility Index (FSI). If applied correctly, the FSI can assist the AF and DoD in understanding its wildfire risk and

facilitate better informed land management decisions in the landscape in and around our installations.

Methodology and Results

Having identified wildfire in the WUI as the hazard, this thesis focuses on providing a tool for understanding the likelihood of the hazard as part of a risk assessment. In doing so, it demonstrates the utility of fusing data from multiple sources, including remote sensing data, in a GIS to facilitate decision making. Mountain Home Air Force Base in Idaho and its surround, pictured below in Figure 1 and site of the large Kinyon Road fire in July 2012, was chosen as the initial application area for this tool. The tool was developed and executed in Esri's suite of GIS software, including ArcMap and Arc Catalog.

Mentioned above, the FSI, described at length in Chapter 2, is applied in this tool to assess the wildfire hazard. The FSI was chosen because, unlike current state of practice for wildfire risk assessment, it was designed to assess wildfire risk using only remotely sensed data (5:140). Further pushing the current state of practice that uses imagery with a 1 km resolution, Landsat 8 with its 30 m resolution is the primary data source used to calculate the FSI. Calculating the FSI requires the use of a regression equation relating remote sensing data to ground fuel conditions, as well as area average values for surface temperature and fuel conditions. The regression equation was developed and tuned for the fire season in the high desert of Mountain Home AFB and area averages were found, together using multiple data sources. The calculated FSI is not



Figure 1: “A six-ship formation of F-15C Eagle and F-15E Strike Eagles fly over Mountain Home Air Force Base Oct. 13. (U.S. Air Force photo by Master Sgt. Kevin J. Gruenwald)” #1 (4)

particularly useful on its own. Chapter 3 describes techniques for data assessment and sharing only made possible with fusion in a GIS. These techniques include altering symbology, working with a basemap, removing and replacing data, using elevation data and its derivatives, and creating maps.

Eight datasets were used not only to tune and build the tool, but also to assess and share the results. The datasets include:

- Landsat 8
 - Band4 – Red
 - Band 5 – Infrared (IR)
 - Band 10 – Thermal IR
 - Quality Assessment (QA) Band

- National Fuel Moisture Database (NFMD)
- Remote Automated Weather Station (RAWS) archive in the Real-time Observation Monitor and Analysis Network (ROMAN)
- NFDRS Fuel Model Map
- United States Geological Survey (USGS) Gap Analysis Program (GAP) Land Covers
- Environmental Protection Agency (EPA) Ecoregion Classification
- USGS National Elevation Dataset (NED)
- USGS US Topo

Each dataset, why it was chosen, and how it was used is discussed at length in Chapter 3.

While the Landsat 8 data can be considered pure remote sensing data, many of the other data products are fusion products themselves, created in part with remote sensing data; this will become apparent when individually introduced. The single attribute that relates all these datasets is location, which is why using a GIS is so powerful. Several datasets are also related by a second important attribute, time, which was necessary for building the regression equation.

The results of the fusion process, shown in Chapter 4, were striking. The Landsat 8 data responded well to the FSI calculations. The effects of topography are readily apparent and used as an initial qualitative validation of the results. Having a dataset with the 30 m resolution is game-changing, providing a view of the landscape not seen in the state of practice; without the data, there is no remote sensing solution for the WUI.

Assumptions, Scope, and Limitations

The goal of this thesis is to demonstrate the utility of fusing remote sensing data in a GIS for decision support. This demonstration does not include completing a formal hazard risk assessment of wildfires on military installations (explored in Chapter 2).

Rather, it provides a tool for understanding part of the risk equation, the condition of fuel in the wildland both on and off base. It will not consider the effects of other hazards in relation to the wildfire risk and will not proscribe particular mitigation efforts.

Landsat 8 has only flown for just over a year. As such, characterization of the sensors is ongoing. While this first attempt produced very reasonable results, it is only the first step toward an operational decision support tool. Future work is outlined in Chapter 5 to further this work. Finally, like any decision support tool, the emphasis is on support, and it is intended to be used in conjunction with local knowledge and other decision support tools that consider other aspects of any given problem.

Implications

As computer networks and processing power continue to grow, so do opportunities for data fusion. To take advantage of today's operating environment, we need to think about how our data will be used, even if unforeseen. From a systems engineering perspective, these are unknown stakeholders. But the stakeholders do have a known requirement: good data with good metadata in standard formats. GIS systems allow for spatial data to be analyzed and fused outside of the originally dedicated stovepiped system. This requires following data documentation standards for producing good metadata.

Use of the method presented here for assessing wildfire risk in the WUI does not end with the Air Force or DoD. It is applicable to emergency managers and municipal park directors in towns across the country, land managers for institutions nestled in the

WUI such as universities and private preservation groups, and ranchers working vast tracts of wildland out west to name a few. Further development is of benefit to the emergency management community as a whole.

Thesis Overview

The remainder of this thesis is presented in the four following chapters. Chapter 2 is a literature review. It takes a look at remote sensing and GIS before turning to wildfire, and most importantly, the FSI. Chapter 3 presents the methodology. The data incorporated, equations used, and analytic processes are all described chronologically as they were included and executed. Chapter 4 shares and analyzes the results of the Chapter 3 efforts. Chapter 5 concludes with a final discussion of the effort and outlines future work.

There are also several appendices. Appendix A provides further background information on wildfire behavior and NFDRS. Appendix B is a repository of web resources, including locations for accessing various data sources.

II. Literature Review

Creating a methodology to answer the problem statement from Chapter 1 requires investigating remote sensing, data fusion theory, Geographic Information Systems (GIS), and wildfire. The first three sections in Chapter 2 cover remote sensing, data fusion theory, and GIS. These areas are each large disciplines. Here, only those concepts to help frame and develop a methodology are explored. The second half of Chapter 2 takes a more detailed look at the physics behind wildfires, how fire danger rating is done today, and looks at a few efforts to incorporate remote sensing data into that process.

Understanding these is key to incorporating remote sensing data in a new fusion process in a GIS to create a tool (Chapter 3) that is applicable to the particular challenge of wildfire risk assessment for the military.

Remote Sensing

In Chapter 1, remote sensing was defined as “the art, science, and technology of obtaining reliable information from non-contact imaging and other sensor systems about...physical objects and processes through recording, measuring, analysing, and representation” (1:3). “Remote sensing” is a relatively new term. It was coined by the U. S. Office of Naval Research in the 1960s (6:1). But its documented roots go back to Aristotle’s *Problems* around 350 BC in which he discusses the process of optically projecting images. Scholarship and scientific advances through the centuries eventually led to the development of the photographic process in France by Louis Daguerre in 1839,

with metal plates and silver iodide (7). Two individuals, Colonel Aimé Laussedat of the French Army, and Albrecht Meydenbauer, a German construction surveyor, working independently developed what would become known as “photogrammetry”—the “technique of performing indirect measurement by means of photographic images”—in the 1850s and 1860s (7:506). The U. S. would finally explore and utilize the methods in 1894 with the commissioning of mapping the Canadian-Alaska Territory border (7). Photogrammetry and photography were developing into what they have become today, and the field of remote sensing now spans the entire electromagnetic spectrum. Remote sensing also encompasses acoustics, near acoustics, and gravitational and magnetic fields. This thesis makes use of remote sensing in the electromagnetic spectrum. Further details on the theory and physics of remote sensing can be found in Rees’s text, *Physical Principles of Remote Sensing* or any other suitable text on remote sensing (6).

Documenting the spatial, spectral, and temporal attributes for remote sensing data in its metadata, along with sensor characteristics and collection conditions, is necessary not only for processing data, but also for repurposing it later. Regularly, data from remote sensing systems are enlisted for purposes not envisioned during design. Ongoing research finds new ways to get information out of the phenomenology. New problems emerge where existing data sources with the right spatial, spectral, and temporal attributes can provide information. Remote sensing has its limits, however. No single system can collect all energy at all wavelengths at all times. Data fusion has emerged to help fill those information gaps.

Data Fusion

In his 2013 article reviewing data fusion techniques for The Scientific World Journal, Federico Castanedo states, “Data fusion is a multidisciplinary area that involves several fields, [making it] difficult to establish a clear and strict classification [of techniques]” (2:2). He goes on to describe five methods of classifying data fusion techniques. I found Dasarathy’s system particularly useful for discussing remote sensing in GIS for decision support because it is focused on the different inputs and outputs of a data fusion activity and not on the method of fusion employed.

In a 1997 publication, Dasarathy describes five categories of data fusion: data in-data out (DAI-DAO), data in-feature out (DAI-FEO), feature in-feature out (FEI-FEO), feature in-decision out (FEI-DEO), and decision in-decision out (DEI-DEO) (2:2).

Castanedo describes them as follows:

“DAI-DAO: this type is the most basic ... data fusion method that is considered in the classification. This type of data fusion process inputs and outputs raw data; the results are typically more reliable or accurate. Data fusion at this level is conducted immediately after the data are gathered from the sensors. The algorithms employed at this level are based on signal and image processing algorithms. ...

“DAI-FEO: at this level, the data fusion process employs raw data from the sources to extract features or characteristics that describe an entity in the environment; ...

“FEI-FEO: at this level, both input and output of the data fusion process are features. Thus, the data fusion process addresses a set of features with to improve, refine, or obtain new features. This process is also known as feature fusion, symbolic fusion, information fusion, or intermediate-level fusion; ...

“FEI-DEO: this level obtains a set of features as input and provides a set of decisions as output. Most of the [other] classification systems that perform a decision based on a sensor’s inputs fall into this category of classification; ...

“DEI-DEO: this type of classification is also known as decision fusion. It fuses input decisions to obtain better or new decisions” (2:2).

Let's consider these three levels of inputs and outputs—raw data, features, and decisions—with respect to remote sensing, GIS, and decision support. Remote sensing data is considered raw data for fusion and often categorized by the collected wavelengths and/or collection method. Some of the more common types are: visual imagery, imaging and non-imaging infrared (IR), multi- and hyperspectral imaging, millimeter wave, radar, and lidar (light detection and ranging). One or more are fused together in feature-level processing to create features. Several of the datasets used in Chapter 3 are feature datasets, particularly the United States Geological Survey (USGS) Gap Analysis Program (GAP) Land Covers, and the USGS National Elevation Dataset (NED). The NFDRS Fuel Model Map and the Environmental Protection Agency (EPA) Ecoregion Classifications are examples of data from FEI-FEO fusions. These datasets are described in further detail in Chapter 3. Finally, we reach decision-level processing. FEI-DEO is where you see “pattern recognition and pattern processing” (8:9). An example of this in a GIS is a mapping application finding navigation routes from one location to another. When one route is chosen as the best option, DEI-DEO fusion has occurred. At any level, no matter the category of data fusion, there can be enough information aggregated for making a decision. The purpose of a decision support tool is to provide that information. In the next section, we look at GIS and how the platforms collect, store, and represent data, as well as enable data analysis, fusion, and sharing.

Geographic Information Systems

In Chapter 1, a GIS was defined as a type of information system that tracked the locations of events, activities, and things (3:4). A GIS can also be defined as: “a computerized tool for solving geographic problems,” “a spatial decision support system,” “a tool for revealing what is otherwise invisible in geographic information,” and “a tool for performing operations on geographic information that are too tedious or expensive or inaccurate if performed by hand” (3:16). A GIS can be different things to different user bases, owing to its power and versatility. For this thesis, a GIS is used as a tool to create, store, analyze, and share spatial information for decision support. This will be demonstrated by addressing the problem of wildfires on and around military bases located in the WUI. In this section, we explore a few of the many concepts encountered when employing a GIS for decision support. A discipline unto itself, there is much more about GIS beyond what is briefly presented here. The text *Geographic Information Systems & Science* by Paul A. Longley, et al. is recommended as a place to start (3).

GIS Data

There are really two parts to any GIS dataset: the digital spatial data and the metadata that accompanies it. While the digital spatial data gets most of the attention, the metadata is of equal importance. A discussion of each follows.

Digital Spatial Data

There are two ways of digitally representing spatial data: with rasters and with vectors. “Rasters...divide the world into arrays of cells and assign attributes to the cells” (3:88). Vectors represent data with points, lines, polylines, and polygons. Collectively,

these are known as shapefiles. There are advantages and disadvantages to both methods of representation that depend on the volume of data, the data source, the resolution needed, how the data will be used, and the software in use (3:89). Despite those, remote sensing data is usually stored as a raster. The feature level data from fusion can be found represented as a raster or a vector.

There are several considerations regarding the accuracy of these representations encountered when working with these spatial data. First, vector data can give an apparent level of accuracy that, in truth, does not exist. For example, if the location of a weather station is only recorded to the nearest second of latitude and longitude, the point that represents its location in the data may not be the actual location of the station. Vectors can also create a discrete delineation where in reality there is a transition or regular change. Classic examples of this are the lines representing a coastline or polygons outlining an ecoregion. A similar situation occurs with raster data where a cell is assigned discrete classification. An area may be classified as forest because forest covers the largest share when in reality the area contains some forest and some open meadow. A continuous raster can conceal extremes. A raster of elevations may give an average elevation for the cell area or be the value of a sampled point within the cell's area. In reality, there are points higher and lower within the area covered by the cell; this can conceal terrain features. All these potential sources of error come down to scale. Generally, as the cartographic scale increases, these errors grow. It is important to develop a methodology that considers these accuracy issues and minimizes the associated errors in analysis.

Metadata

All spatial data is accompanied by metadata that provides information about its contents. Metadata is what is used to determine the suitability of a particular dataset for a particular use. It must also contain all the information a user would need to work with the spatial data (3:281).

There are documentation standards for metadata. Executive Order (EO) 12096, among other things, tasked the Federal Geographic Data Committee (FGDC) in 1994 with the development of “technology, policies, standards, and human resources necessary to acquire, process, store, distribute, and improve utilization of geospatial data” (9). This included the standardized documentation of geospatial data. In addition to the Content Standard for Digital Geospatial Metadata, the current federal metadata standard, the FGDC has endorsed other standards, including the *North American Profile (NAP) of ISO 19115: Geographic Information - Metadata*. Across the standards, much of the metadata content is similar. Generally, metadata contains: identification information, the data format, data quality information, a spatial reference and coverage information, the dates of collection and publication, details about the data’s entities and attributes, distribution information, citation information including authors and contributors, and contact information.

When considering a dataset for use in fusion activities, attention must be paid to several attributes that should be documented in the metadata. First, all data is collected at a point in time. Over time, data ages, the geography or conditions they represent change. The acceptable age of the data depends on the data. Weather data ages quickly; the locations of roads change more slowly. Second, considering the earlier discussion on the

accuracy of digital spatial information, data quality information must be considered. This describes how the data was collected, any sources of error in the collection method, and the level of accuracy or accuracy standard the data has, and finally scale the data was collected at or intended to be used at. Finally, any copyright or distribution limitations must be understood.

Making the Earth Flat

The earth is not flat. However, the focal plane arrays, paper maps, and computer screens that collect data and render the round earth are. The last two subjects to touch on are transformations and the art of mapmaking.

Transformations

The metadata for well documented data sets contains the information about the projection used to render the data as well as the datum (the origin from which measurements are made). Projections are planar, cylindrical, conic, or a combination. Two common datums encountered are North American Datum (NAD) 1983 and World Geodetic System (WGS) 1984. The Global Positioning System (GPS) Satellites use WGS 1984. Calculations are used to transfer from one projection and datum to another and to render the data layers together. Errors in analysis can result from improper or incomplete transformations. Many GIS handle transformations internally, including Esri's suite of products, provided the program can properly read the necessary information from the metadata. If not, more effort is needed to define the transformations.

Maps

GIS have their roots in mapmaking from efforts to automate parts of the map printing process during the advent of computers. While a GIS is much more than a program to display and print maps, the fact that cartography is both an art and a science has not changed with the arrival of the GIS. What data and features are included and how they are symbolized on a map depends on the data, audience, and intended use. With a GIS, making adjustments for this is relatively easy. In the effort to store and share information, most maps are composed of several common pieces: a title, map body, inset map, legend, scale, direction indicator, and metadata (3:307). While the map body is the focus of the map, the other pieces are necessary to communicate with and give context to a user.

With an understanding of remote sensing, data fusion, and GIS, let's turn to applying these to the problem of wildfire in the WUI for the AF and DoD. Indeed, this problem is not unique to the AF and DoD, but perhaps it is not thought of as the common issue it is.

Wildfires, the Air Force, and the Department of Defense

The Air Force and our sister services are no stranger to wildfire, on base and off, naturally or human started. Some make the national evening news, and others only get a mention from the local news outlets. Table 1, below, summarizes some wildfires from the

past two years as reported in InciWeb and news outlets to illustrate the breadth of the DoD issue with wildfire in the WUI.

Table 1: 2012-2013 DoD Wildfires

Fire	Date	Size (acres)	Location
	Notes		
Range 14	09April 2012	300	Joint Base McGuire-Dix-Lakehurst, NJ
	Threatened several homes (10; 11)		
(no name)	15 May – Mid June 2012	2,800	Eglin AFB, FL
	Prescribed burn reignited in a swamp on base (12; 13)		
Waldo Canyon	23 June-10 July 2012	18,000	Pike National Forest and onto US Air Force Academy (USAFA), CO
	USAFA partially evacuated; firefight cost \$16,000,000 (14)		
Kinyon Road	07-13 July 2012	235,000	Around and onto Mountain Home AFB
	I-84 closed; started by lightning (15; 16)		
Black Forest	11-20 June 2013	14,000	Black Forest, CO near USAFA
	500 structures destroyed; local military installations joined firefight; AF civilian and contractor died in their home (17; 18; 19)		
Stuart Creek 2	19 June past 19 August 2013	87,000	Fort Wainwright, threatening Eielson AFB
	Army started the fire on Yukon Training Area with artillery during training activities while a Red Flag Warning in effect; 1,200 area residents evacuated; firefight cost \$5,500,0000 (20; 21)		
Deluz	05-09 October 2013	2,200	Camp Pendleton Marine Base
	Base housing evacuated; base hospital forced to transfer several patients and close its doors to new (22; 23)		

Wildfires do not have to be large and “out west” to disrupt the mission and endanger personnel and property. The only requirement is having some wildland with fuel that can ignite and burn. In Chapter 1, we stated the AF and DoD are impacted by wildfire. Looking at these incidents over the last two years alone, it is obvious how pervasive wildfires and their threat are. We manage wildlands and abut wildlands. Our

mere presence creates a WUI. Fire danger ratings impact our ability to train, test, and operate. Sometimes, despite best efforts, our activities start wildfires. However they start, we fight and manage fire incidents both on and off base. Our personnel and ultimately the mission are impacted by area wildfire activity, making wildfire, in turn, part of our mission.

Emergency Management

Tackling wildfire on military bases is not uncomplicated. To frame the approach, let's first look at wildfire in the WUI through the lens of emergency management

Response and recovery activities are first to mind when thinking of emergency management, such as the cleanup and rebuilding of a neighborhood after a tornado. Instead, emergency management begins with mitigation efforts, and part of mitigation is a process known as hazards risk management. As the old adage goes, "an ounce of prevention is worth a pound of cure," and emergency management is no different. This section examines hazards risk management and introduces fire danger rating and how that dovetails into hazards risk management.

Hazards Risk Management

George Haddow, with coauthors Jane Bullock and Damon Coppola, wrote a text titled Introduction to Emergency Management. Haddow's work with the Institute for Crisis, Disaster, and Risk Management at George Washington University is considered by many to be at the forefront of emergency management. Haddow writes that while different organizations have enumerated different steps for risk management, hazards risk

management is generally broken into four steps: 1, Hazard Identification; 2, Risk Assessment; 3, Combined Hazard Risk Analysis; and 4, Hazard Risk Treatment (24:59). Let's take a look at each of these and how this thesis addresses each.

First, there is hazard identification. Haddow cites the National Governors Association definition of a hazard as a "source of danger that may or may not lead to an emergency or disaster" (24:29). The hazard considered here is wildfire, specifically wildfire in the WUI. Identifying the hazard will help land managers better understand the hazard as they consider land management options and develop a land management plan.

Next is the risk assessment. Haddow defines risk as "the likelihood of the hazard leading to an actual disaster event and the consequences of that event should it occur" (24:29). A true risk assessment takes into account two things: likelihood and consequence. This thesis cannot complete an entire risk assessment. Chapter 3 will provide a method for better understanding the likelihood. The likelihood of a wildfire will change constantly, its quantification is complicated, and collection of field data over a large area is labor intensive. That is where the remote sensing comes in. Assessing consequences is beyond the scope of this thesis. In Chapter 4, it is pointed out how working with remote sensing data in a GIS can assist in assessing consequences, however, not all consequences have a spatial element and cannot be analyzed in a GIS.

The third step is the combined hazard risk analysis. Here, multiple hazards are considered together, both natural and man-made. While this activity is important for any installation commander, it is also beyond the scope of this thesis.

The final step of hazard risk management is the hazard risk treatment. Haddow defines it as, "the process by which either the likelihood of a...risk is reduced or

eliminated, or measures are taken to reduce the impacts of those hazard events that do actually occur” (24:62). An entire field of research and activity has emerged to mitigate wildfire in the WUI. Building codes, for example, have been updated in many western states. Local fire departments conduct prescribed burns in risky areas with high fuel loads. This thesis, however, will not specify risk mitigation activities.

Looking back at the risk assessment, Haddow cautions, “it can be impossible to extrapolate exact numerical values that are representative of these two factors [risk likelihood and consequences]” (24:60). He goes on to advocate the use of qualitative methods to facilitate the risk assessment process and overall hazards risk management. The aim of this thesis, it is not to provide an exact quantitative assessment of wildfire likelihood, but rather a tool to help commanders and their staff make informed policy and decisions on base operations and land management.

Fire Danger Rating

The authority on fire danger rating in the United States is the National Wildfire Coordinating Group (NWCG). The NWCG is an interagency group chartered to “[provide] national leadership to develop, maintain, and communicate interagency standards, guidelines, qualifications, training, and other capabilities” for wildland fire program management (25:2). The NCWG consists of eight member organizations: the Bureau of Indian Affairs (BIA), the Bureau of Land Management (BLM), the U.S. Fish and Wildlife Service (USFWS), the National Park Service (NPS), the U.S. Forest Service (USFS) (by both Fire & Aviation Management and Fire Research), the U.S. Fire Administration (USFA), the National Association of State Foresters (NASF), and the

Intertribal Timber Council (ITC). In their documentation of the National Fire Danger Rating System (NFDRS),—discussed later at length—the NWCG first identifies what is meant by fire danger as the “sum of constant danger and variable danger factors affecting the inception, spread, and resistance to control, and subsequent fire damage; often expressed as an index” (26:73). They go on to explain that “fire danger ratings are typically reflective of the general conditions over an extended area often tens of thousands of acres...fire danger ratings describe conditions that reflect the potential, over a large area, for a fire to ignite, spread, and require suppression action” (27:4).

As we will see in the next section, wildfires are complex, and assigning a fire danger rating is equally so. The NWCG describes fire danger rating systems as a “complex mixture of science, technology, and local experience,” and go on to enumerate five key components of a system:

- “a. Models representing the relationships between fuels, weather, and topography, and their impact on fire business.
- “b. A system to gather data necessary to produce the rating numbers.
- “c. A processing system to convert inputs to outputs and perform data analyses.
- “d. A communication system to share the fire danger rating information between entities.
- “[and] e. A data storage system to retain data for historic reference” (27:4-5).

The system that contains all of these components is NFDRS.

Fire danger rating is a data fusion process akin to Haddow’s risk assessment step in hazards risk management. “The various factors of fuels, weather, topography, and risk are combined to assess the daily fire potential on an area” (27:4). As discussed in the previous subsection, this risk assessment process can be both quantitative and qualitative.

Here, at the end of a very scientific process, a qualitative assessment is given as an adjective rating: Low, Moderate, High, Very High, Extreme. The fundamental purpose of risk assessment is to provide decision support. The NWCG explains that the fire danger rating is merely a decision making tool, that “it must be considered along with the manager’s local knowledge of the area and consequences of [a] decision” (27:4). The decision support tool presented in this thesis is designed to augment existing decision support tools, like NFDRS, by looking at the unique problem set that is the WUI and providing managers better local knowledge.

Wildfire

The problem of wildfire has been studied for decades in the US and abroad. From ignition to suppression, physics underlies much of the work. Names like Robert E. Burgan, Richard C. Rothermal, George M. Byram, Michael A. Fosberg, Larry S. Bradshaw, John J. Keetch, and John E. Deeming, along with others, appear over and over again in the literature. As we move forward, we will look at their legacy, understanding fire basics and looking at a few of the systems and indices used by land managers today. Before we jump into that, however, let’s take a second look at the WUI as we will revisit it often when discussing wildfire.

The Wildland Urban Interface

The National Wildfire Coordinating Group (NWCG) defines the WUI as “the line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels” (26:186). The Library of congress has a

definition that includes the land within a half mile of the comingling to be part of the WUI (28:276). The term WUI is often associated with wildfires, but it can also be used in the discussion of other ecologic and environmental issues. The WUI is of particular concern because “fires occur[ing] in or near the wildland-urban interface, [affect] both natural and built environments and [pose] a tactical challenge to firefighters concerned with the often conflicting goals of firefighter safety and property protection” (24:43). Many military installations fall within the WUI by nature of their contents and neighboring land.

Many more terms besides WUI appear in the literature. Some distinguish wildland from uncultivated farm and ranch land. A common distinction seen in wildfire discussion is between interface and intermix. Interface is used to describe a hard line of development where structures abut vegetation. Intermix is used to describe areas where development and vegetation intermingle. In the Federal Register, a structure density is defined to go along with those definitions: three or more structures per acre in an interface, one or more structures per forty acres in an intermix (29). Depending on the conversation, these words may be but are not always important. When looking at mitigation options, fire behavior, and considering fire suppression tactics, they are very important. Here, a possible distinction for remote sensing must be considered.

All the energy received by a remote sensor comes from whatever falls within its field of view. When looking at the WUI, some of the energy is coming from the vegetation, some from manmade structures. Data with a 1 km x 1 km pixel size cannot differentiate vegetation from structure. At this resolution, an intermix may contribute more energy from vegetation than interface, but that depends on the structure density. As

we will see, many of the remote sensing techniques do not work well in a WUI at this resolution for that very reason. Data with a 1 m x 1 m pixel can differentiate very well, perhaps too well. At this level of detail, individual plants with their individual reflectance values can make calculations cumbersome and data interpretation difficult. At 30 m x 30 m, Landsat data has a history of good vegetation and land cover analysis. At this resolution, a home or parking lot is differentiable from a wooded lot. Interface or intermix, structures can be masked from the analysis yet the resolution is large enough the surrounding vegetation can be considered as a whole landscape and not as individual plants.

It is not necessary to differentiate between and interface and intermix for this thesis. As stated in Chapter 1, Landsat 8 data will be used for this thesis, so the remote sensing resolution does not require it. As will be discussed more in following sections and in Chapter 3, wildfire behavior is not modeled, nor are suppression techniques considered for this thesis; therefore, the simple WUI definition will suffice and encompass both interface and intermix.

The National Fire Danger Rating System

NFDRS was developed by the U.S. Forest Service and first launched in 1972. Several updates later, it is still used today across federal and state agencies. NWCG wrote a users' guide and independent study course that distill much of the information in the U.S. Forest Service publications (27; 30). In a previous subsection, NFDRS and the five components of fire danger rating were introduced. Here, the development of NFDRS, how it is structured, and the system outputs area briefly introduced with further

detail in Appendix A. That is followed by reflection on how it is employed today, particularly in relation to the WUI.

Fire Danger Rating Today: Reaching the State of Practice

According to the NWCG, research in fire danger rating began in 1922 (27:2). “By 1958, there were at least eight different systems being used by the Forest Service plus numerous other systems being used by state and private protection organizations” (27:2). The systems were highly dependent on local knowledge and experience. Work began to create a single fire danger rating system that incorporated risk, ignition, spread, and fuel energy. The system was to address the issues with the numerous early 20th century versions. It was to be: “a. scientifically based; b. adaptable to the needs of local managers; c. applicable anywhere in the country; and d. reasonably inexpensive to operate” (27:5). In 1972, a trial version of NFDRS was released. Calculations were done by hand and with nomograms and lookup tables. “In 1975, an automated version of the NFDRS was made available on a nationally accessible time-share computer called AFFIRMS (Administrative and Forest Fire Information Retrieval and Management System)” (27:2-3). The current version of NFDRS was released in 1978 after a series of changes and updates. Over the next decade, it was realized the 1978 models were less accurate for the southeastern United States than the western states. A revised version was released in 1988 to better model “how fuel moistures change during periods of drought and precipitation” (27:3). In 1993, the Weather Information Management System (WIMS) replaced AFFIRMS as the automated storage and processing system and is still in use today.

Using WIMS, NFDRS takes a series of inputs (a combination of weather data and field observations), fuses the data, and calculates a series of outputs daily. The graphic below, Figure 2, is from the NWCG and tracks the NFDRS inputs, intermediate calculated values, and output data. The calculations are done for a fire danger rating area, “a geographical area of generally homogenous fuels, weather, and topographic features, tens of thousands of acres in size” (27:12).

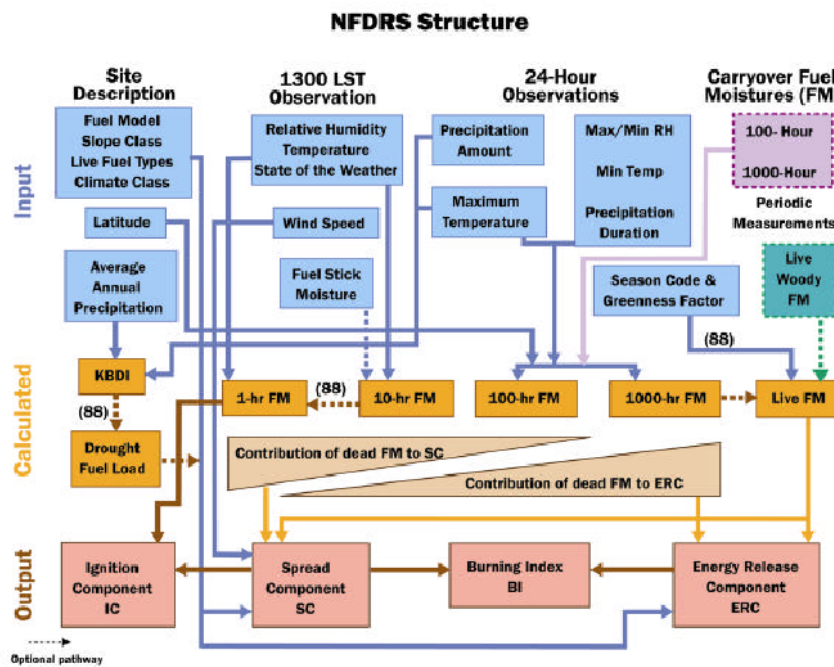


Figure 2: NFDRS Structure (27:38)

NFDRS outputs can be broken into “intermediate calculations that serve as the ‘building blocks’ for the next day’s calculations and the indices and components that actually measure the fire danger” (27:21). Intermediate calculations are the fuel moistures (described earlier): herbaceous live fuel moisture, woody live fuel moisture, and the four classes of dead fuel moisture. These calculations require daily weather

inputs. They are also checked and calibrated not less than monthly by collecting and measuring field specimens. NFDRS calculations output five indices and components as well as an adjective fire danger rating.

The NFDRS outputs are used for many land and fire management decisions. The NWCG identifies several in their documentation: determining a necessary staffing level for wildfire response; preplanning emergency response actions; guiding restrictions on industrial and public use activities; assisting in wildland fire use go/no-go decisions; communicating fire danger conditions to fire crews, emergency response personnel, and the public; assessing regional response preparedness levels; and supporting funding requests based on comparison to historical conditions. (27:28-33)

The Wildland Fire Assessment System (WFAS) (see Appendix B for web resources) uses the NFDRS calculations done by WIMS, including the fire weather data, and creates national maps daily using inverse square interpolation on a 10 km grid (Cite 31). WFAS admits this method has its limitations. Looking at these products gives a sense of what NFDRS does and makes the previously discussed shortfalls in applying NFDRS at a large cartographic scale.

Two examples of fire danger rating products from 15 August 2013 and 15 October 2013 are below in Figure 3 and Figure 4. Both days are weekdays. The locations of the reporting weather stations are indicated with triangle markers, and the NFDRS adjective fire danger rating is mapped. There are several observations to glean.

First, notice how large an area the fire danger ratings are applied over. This has to do with the distribution of reporting stations and the use of the inverse square

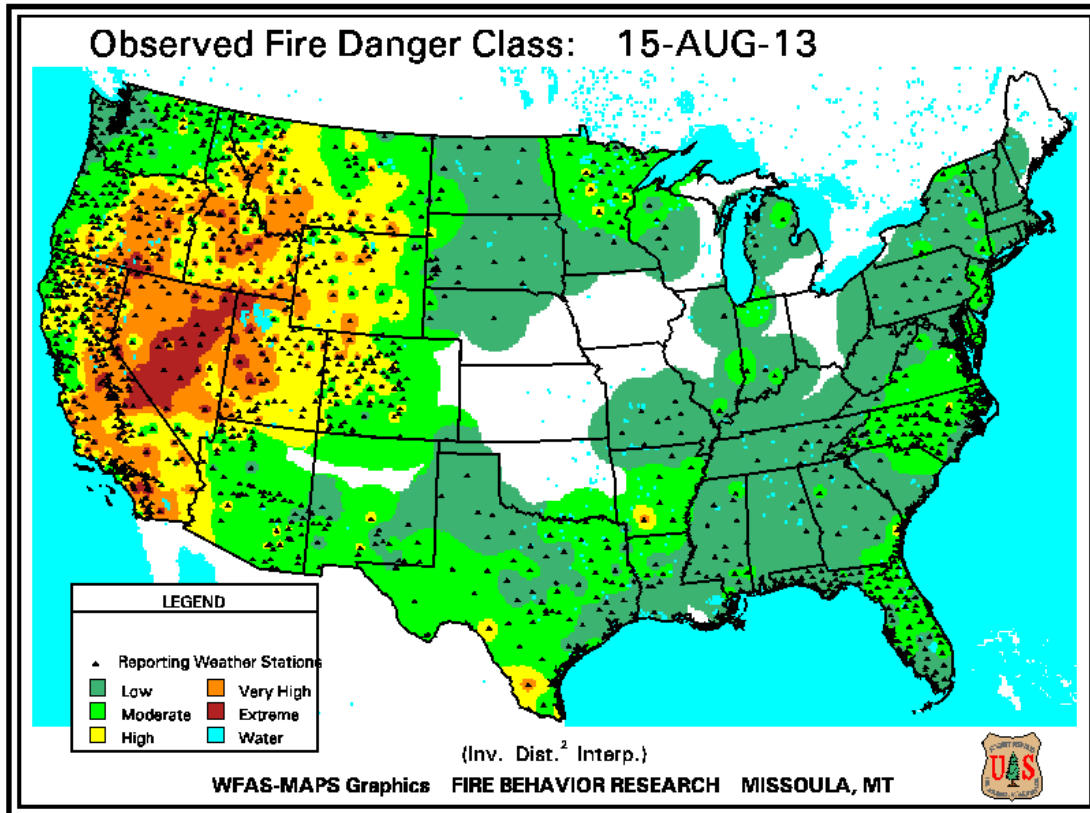


Figure 3: WFAS National Fire Danger Rating, 15 Aug 2013 (32)

interpolation method. Potential disparity between actual conditions and the assigned fire danger grows as distance to the nearest reporting station grows.

Second, notice the difference in the number of reporting stations between the August and October maps. The system is dependent on regular, sometimes manual, data entry to produce outputs. While the majority of the weather reports come from RAWs, they still require maintenance and upkeep to keep them calibrated, collecting, and reporting weather information. Many of the remote stations are not open year round. Others only submit full reports on weekdays. Two maps are compared in Figure 5 below, one from Sunday, 15 December 2013, and one from Tuesday, 17 December 2013. Fewer stations reported over the weekend.

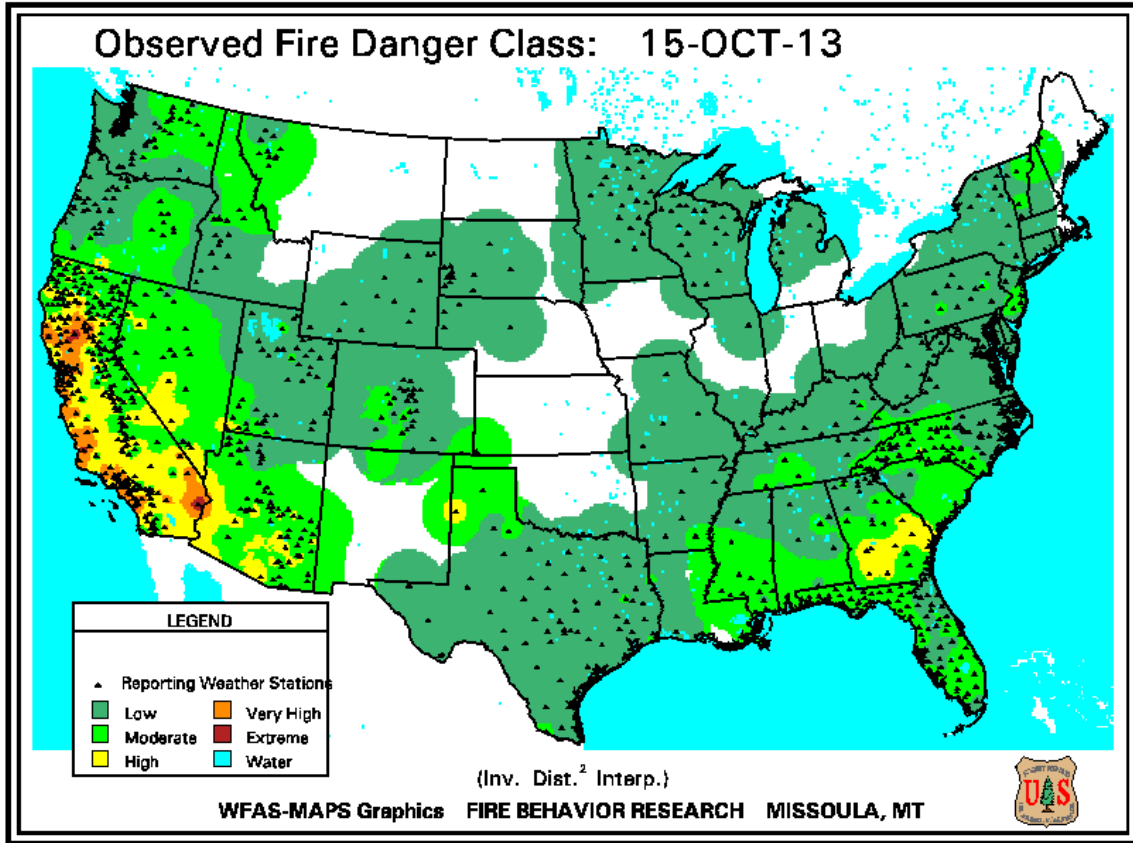


Figure 4: WFAS National Fire Danger Rating, 15 Oct 2013 (32)

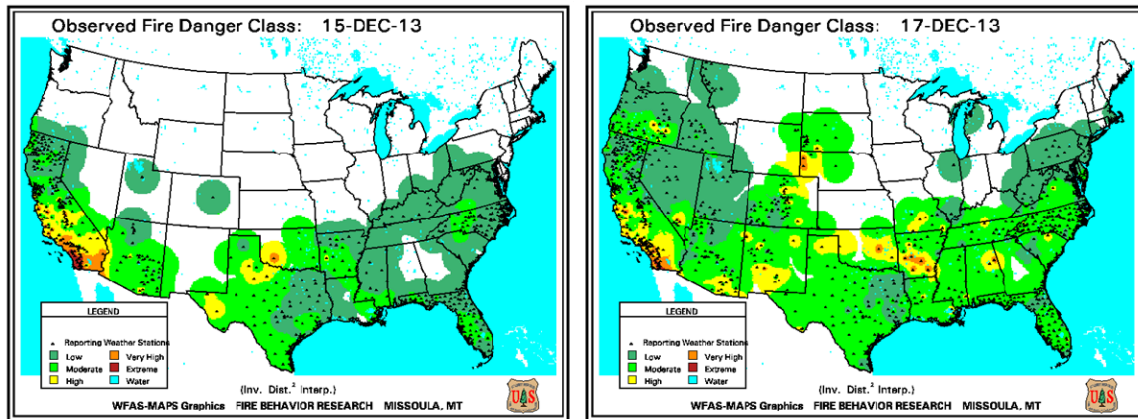


Figure 5: WFAS National Fire Danger Rating, Comparing 15 December 2013 and 17 December 2013 (32)

This year's reporting also appears to have been impacted by the government shutdown from 01 to 16 October. Comparing the Tuesday, 15 October map to one from the end of the week on Friday, we see reporting stations open back up (Figure 6). Comparing 18 October in Figure 6 with 17 December Figure 5, we again see many stations closing down at the end of the fire season, especially in the northern latitudes where there is snow cover.

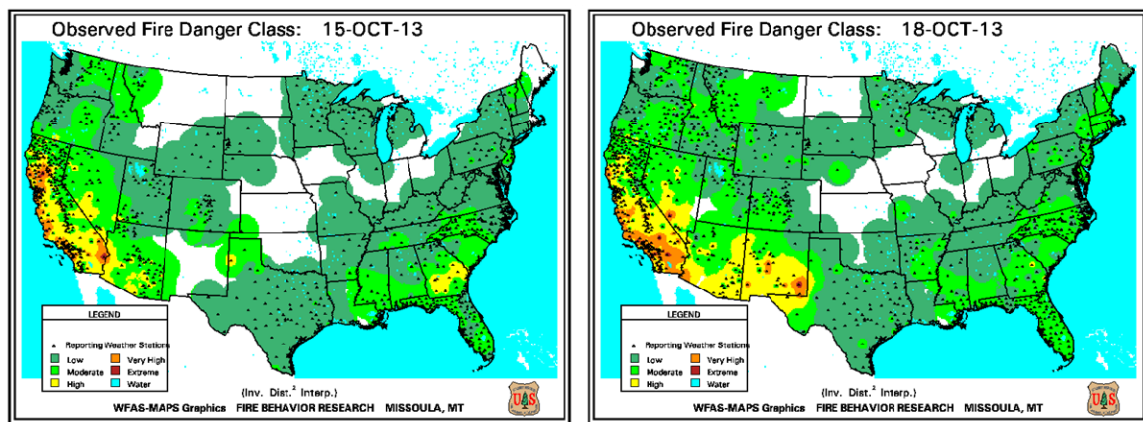


Figure 6: WFAS National Fire Danger Rating, Comparing 15 October 2013 and 18 Oct 2013 (32)

NDFRS outputs are only as good as the input. And while useful, the application is limited. To address this, the use of remotely sensed data has been incorporated into WFAS products. The georeferenced data for some of these are available for download, including the Normalized Difference Vegetation Index (NDVI) and derived products: Visual Greenness, Relative Greenness (RG), and Departure from Average (31). An example of the RG product (Figure 7, below) immediately depicts the power of remote sensing. Detailed information is universally available for everywhere. Properly geotagged, it can be used for further analysis in a GIS system.

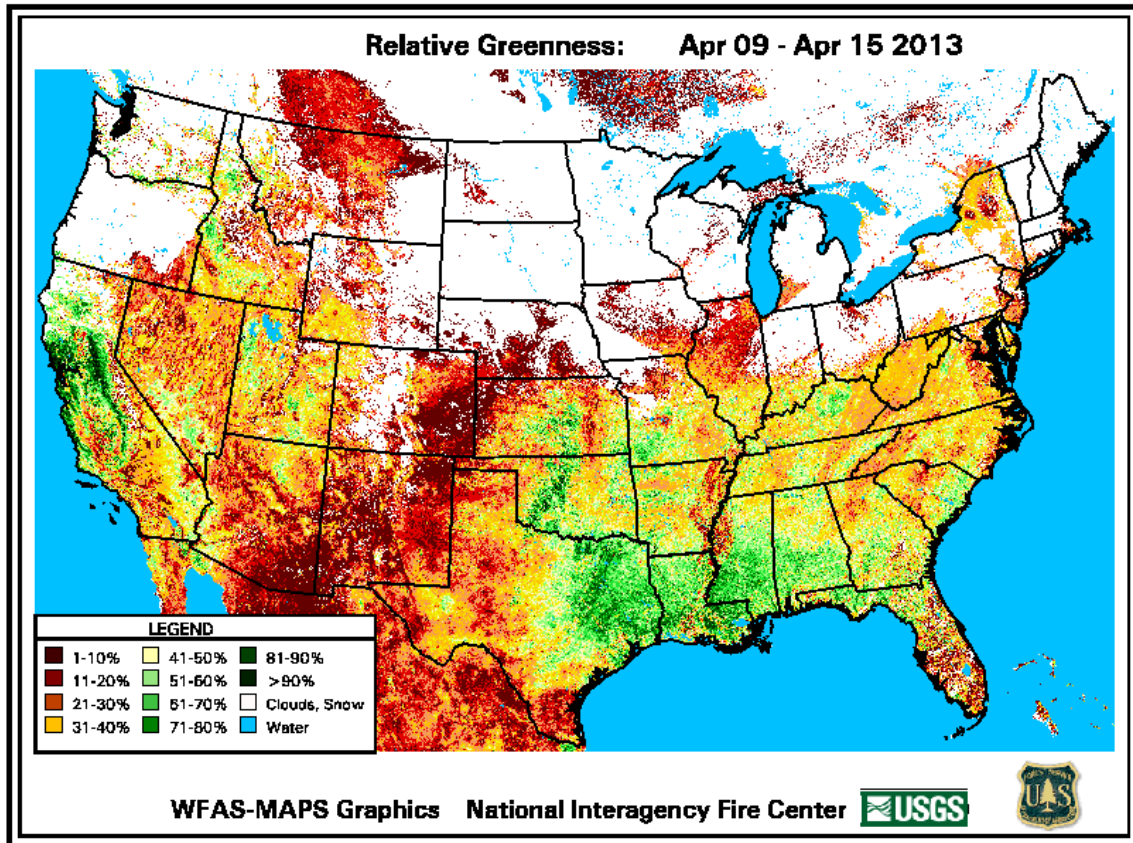


Figure 7: Relative Greenness, 09-15 April 2013 (32)

NFDRS and Wildfire in the WUI

To better understand the applicability of NFDRS to the WUI, it is important to grasp the system’s key underlying assumptions, particularly the first and fourth. The NWCG summarizes them as follows:

- “1. NFDRS outputs relate only to the of an initiating fire, one that spreads, without crowning or spotting, through continuous fuels on a uniform slope.
- “2. NFDRS outputs address fire activity from a containment standpoint as opposed to full extinguishment.

“3. The ratings are relative, not absolute, and they are linearly related. In other words, if a component or index doubles, the work associated with that element doubles.

“4. Ratings represent near worst-case conditions measured at exposed locations at or near the peak of the normal burning period.” (27:6)

Examining these assumptions, it is clear this decision making tool was focused on assessing wildfire risk over large areas, and the NFDRS output fidelity will break down at the larger cartographic scales necessary to assess fire danger in the WUI. Of particular note are assumptions of uniform (from the definition of a fire danger rating area) and continuous fuels and uniform slope. On a much smaller scale the natural vegetation will vary, intermingle, and be discontinuous. Natural vegetation is even more interrupted in the WUI with changes to land use, land clearing, the introduction of planned landscaping, and the construction of structures and infrastructure. Slope, too, certainly does not remain constant, and slope aspect can be an important discriminator of fuel moisture (see discussion of the wildfire behavior triangle in Appendix A).

Simply sub-dividing fire danger rating areas by fuel model, slope class, and aspect is not the answer either, even if solely based on the labor intensive collection and submission of the necessary field observations into WIMS. An entire workforce would be needed to collect and dry the necessary vegetation samples alone, and this ignores the fact that if we want to include remote areas in the subdividing, many of them will take days of hiking to access, even in the conterminous United States. Realizing this, we look at remote sensing for data collection and data fusion in a GIS for risk assessment. Working with remote sensing alone, however, cannot replicate the NFDRS analysis. NFDRS is, as designed, great for a large area and taking into account available

firefighting resources, fire spread potential, and long term trends over the area. It should remain as a decision making tool and part of a Combined Hazard Risk Analysis (Haddow's third step).

Looking back, NFDRS was designed to incorporate risk, ignition, spread, and fuel energy. Common physics underlies much of this. This means remote sensing data can be incorporated and used on lieu of some inputs to physics-based equations, and in a using GIS, data can be correlated by geolocation. Instead of replicating NFDRS, however, the decision support tool must solve land management issues particular to the WUI, namely: identify, quantify, and monitor hot spots—areas of high vegetative stress at higher risk of ignition—and their relationship to the landscape and a whole. In an effort to develop such a tool, we follow an effort to introduce reduce remote sensing into fire danger rating.

Remote Sensing Algorithms for Wildfire

As discussed, NFDRS has its shortcomings as a manual process with a small number of stations collecting data for large areas. To combat this, attempts to incorporate remote sensing to better understand and predict fire behavior and danger began, and they took off in the early 1990s beginning with work by Robert E. Burgan and others. Over the years, dozens of indices have been created to meet that goal, focusing on one aspect or another of fire behavior and fire danger and using disparate mixes of field sample data and remotely sensed data. Here, we will introduce an evolution of four of these indices

relevant for this thesis, beginning with the very general NDVI and ending with the Fire Susceptibility Index (FSI).

Normalized Difference Vegetation Index

One of the earlier attempts to use remote sensing over large areas to understand fire danger and fire behavior was with the NDVI using data from the Advanced Very High Resolution Radiometer (AVHRR) sensors on NOAA's polar orbiting satellites. We look at it here because it underlies many other indices. NDVI is used to assess vegetative greenness as it is "sensitive to the quantity of actively photosynthesizing biomass on the landscape" (33:1). NDVI has also been used for many other activities including agriculture and land cover mapping. NDVI is used to signal drought or other stress to plants, as well as understand where plants are in the annual growing cycle. Hundreds of studies have been done in the past few decades looking at NDVI and correlating its indications. NDVI itself is a very simple calculation (Equation 1), using reflectance values in red and near IR, usually at the top of the atmosphere and corrected for solar angle.

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

Where

NIR	Reflectance in Near Infrared wavelengths
RED	Reflectance in Red wavelengths

The US Forest Service has published two General Technical Reports, 297 and 333, discussing procedures for calculation and use (33; 34). NDVI data is available for download through WFAS, as well as the several products it is used to create.

Relative Greenness

RG, one of the NDVI products, “portray[s] how green the vegetation is compared to how green it has been historically (1989-2003)” (35). RG is calculated pixel by pixel with the following equation (Equation 2) (36):

$$RG = \frac{(NDVI_o - NDVI_{mn})}{(NDVI_{mx} - NDVI_{mn})} \cdot 100 \text{ Relative Greenness} \quad (2)$$

Where

$NDVI_o$	Highest Observed NDVI for 1 Week Period
$NDVI_{mn}$	Minimum Historical NDVI
$NDVI_{mx}$	Maximum Historical NDVI

NDVI is different for each plant species as it progresses through the growing season. RG then helps compare different areas to each other as each plot is compared to its own self.

Fire Potential Index

In 1998, Robert E. Burgan, Robert W. Klaver, and Jacqueline M. Klaver published a paper in the *International Journal of Wildland Fire* introducing their new Fire Potential Index (FPI) (36). “The FPI...was developed to incorporate both satellite and surface observations in an index that correlates well with fire occurrence and can be used to map fire potential from national to local scales through the use of a GIS” (36) There were two goals for the FPI development. First, NFDRS looks at fire danger over large areas, as we have seen. Here, they wanted to go down to a 1 km resolution, but still cover or apply the index over the entire continent (36). Second, Burgan was looking for a simpler implementation than NFDRS (36).

FPI uses several inputs, some remotely sensed, and some from NFDRS. FPI looks at both live and dead fuel moistures and the fractional amount of each in every 1 km by 1 km area (36). To include the fraction of live fuel, RG, as previously discussed, is used from remotely sensed data (36). To include the dead fuel moisture, the 10-hour fuel moisture is pulled from the NFDRS calculations, interpolated between stations, and applied to the fuel model that dominates the area (36). The NFDRS fuel model map was made correlating remotely sensed land covers to the NFDRS fuel models with field test sites (36). The ratio of live to dead fuel is set by a maximum live ratio map created with the maximum NDVI values across the lower 48 states (36). The exact calculations are not presented here as it is not necessary to understand for this thesis work. They are documented in Burgan's paper and on the WFAS website (36).

Burgan reports increased FPI correlates with increased incidence of fire (36). Burgan also states that because FPI "is not a physically based model... [it] requires enough historical data to develop the statistical relationships that can provide fire probability given a specific FPI value" (36). The current FPI forecast maps are available for download from WFAS as an experimental product. Current GIS data sets and historic forecast maps (Figure 8) are available for download through the USGS Fire Danger Forecast – Interactive Viewer (see Appendix B).

Fire Susceptibility Index

In 2006, Swarvanu Dasgupta, John Jianhe Qu, and Xianjun Hao published a paper presenting their new Fire Susceptibility Index (FSI) in a paper titled "Design of a Susceptibility Index for Fire Risk Monitoring" (5). Dasgupta designed a method of

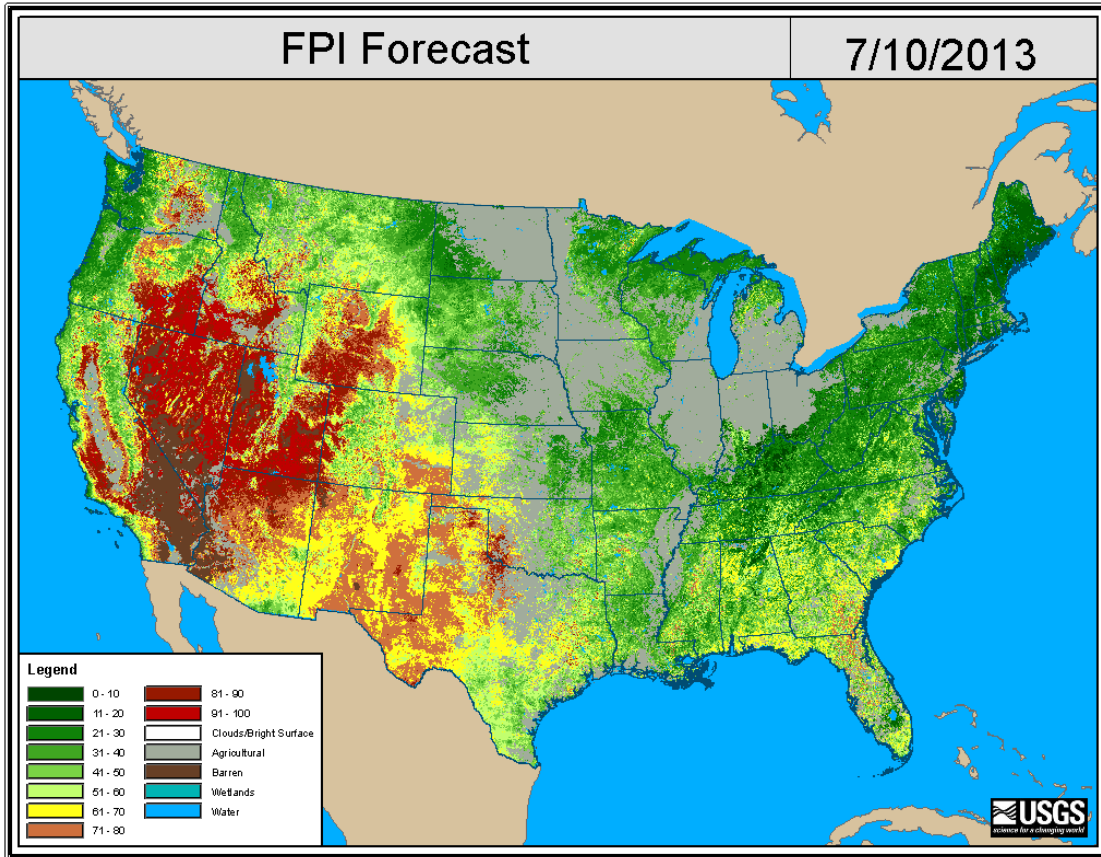


Figure 8: FPI Forecast – Day 1, 10 July 2013 (37)

assessing wildfire risk using only remotely sensed data and validated it against the FPI (5:140). The FSI is “based on the concept of heat energy of preignition” (5:140). “Heat energy of preignition (Q_{ig} , kilojoules per kilogram) can be defined as the heat energy required to bring a fuel from its current temperature to ignition temperature and can be estimated as the sum of: 1) the heat required to raise the temperature of moisture contained to the boiling point (373 K under standard atmospheric pressure); 2) the latent heat required in evaporating the moisture content; and 3) the heat required to raise the

temperature of the resulting dry fuel to ignition temperature” (5:141). Dasgupta expresses it as:

$$Q_{ig} = M_f [C_{pw}(373 - T_f)] + M_f V + C_{pd}(T_{ig} - T_f) \frac{KJ}{Kg} \quad (3)$$

Where

$C_{pd} \approx 1.7 \text{ KJ} \cdot \text{kg}^{-1} \text{K}^{-1}$	Specific Heat Dry Wood
$C_{pw} \approx 4.187 \text{ KJ} \cdot \text{kg}^{-1} \text{K}^{-1}$	Specific Heat Water
$T_{ig} \approx 600 \text{ K}$	Ignition Temperature of Wood
$T_f \approx ST$	Fuel Temperature
$M_f = \frac{FMC}{100}$	Fractional Fuel Moisture Content
$V \approx 2258 \text{ KJ} \cdot \text{kg}^{-1}$	Latent Heat of Vaporization of Water

(5:141)

Remote sensing data is used to estimate the FMC and T_f for live fuels. T_f was approximated with surface temperatures, ST, from MODIS Land Surface Temperature (LST) (5:142). The sure way to acquire current live fuel moisture is to collect field samples and calculate the difference in weight before and after oven drying; this is a labor intensive method and sampling can be sparse. Work to understand remote sensing data and accurately model live fuel moisture content continues. Dasgupta uses a linear regression equation (Equation 4), tuned for the state of Georgia, to relate the remote sensing data to FMC (5:141). The paper gives a detailed explanation of how he used the NFDRS live woody FMC reported by the weather stations and the remote sensing data to develop the least square regression equation. The method presented in Chapter 3 is based on Dasgupta’s method.

$$FMC_{woody} = 19,059 \cdot \left(\frac{NDVI}{ST} \right) + 74 \quad (4)$$

The NDVI (Equation 5) is calculated using MODIS band 1 (red), $\rho_{0.65}$, and band 2 (near IR), $\rho_{0.86}$. (5:142).

$$NDVI = \frac{\rho_{0.86} - \rho_{0.65}}{\rho_{0.86} + \rho_{0.65}} \quad (5)$$

Dasgupta uses NDVI/ST instead of just the NDVI, as presented above in a previous subsection (5:140, 142). Dasgupta reports, “Improvements in live FMC estimations have been observed with incorporation of satellite-derived [ST] since ST increases in drier plants due to reduced evapotranspiration” (5:140). In other words, a higher ST diminishes the perceived greenness assigned by the NDVI, and a lower ST amplifies it, yielding better estimations in live FMC.

Dasgupta then creates the unit-less index (Equation 6) using average Q_{ig} based on an average FMC and T_f for the area from weather stations (5:141):

$$FSI = FSI_L = \left[\frac{Q_{igavg} - Q_{ig}}{Q_{igavg}} \right] \cdot 100 \quad (6)$$

The index is tunable by selecting FMC and T_f for a particular fuel, ecoregion, and time of year (5:141). By holding FMC and T_f constant in turn, Dasgupta finds “the contribution of live FMC to FSI_L is relatively higher than fuel temperature” (5:141). This is good because surface temperatures change throughout the day, and satellite overpasses are not necessarily at the same local time every time. If the index was more sensitive to temperature, comparing results from multiple collections would be more difficult.

Equation 6 sets the FSI equal to FSI_L using only the live FMC derived from remotely sensed data. Dasgupta presents an unattempted method for including dead FMC in an FSI_D , but it was not included in the index because remotely sensed data

collection is difficult as the fuel is often hiding below a canopy of live fuel (5:141). For that same reason incorporating dead FMC will not be attempted in this thesis.

There are two advantages to the FSI. First, once the regression equation is built, the FSI can be computed using only remotely sensed data. Second, because the FSI is soundly based on the heat energy of preignition, a variable that shows up in NFDRS and Rothermel's wildfire spread model (not discussed in this thesis), it can be used as input for further analysis such as calculating probability of ignition and modeling fire behavior (5:140).

Dasgupta also discusses a shortcoming of his work: the index did not do well in urban areas because foliage makes up less of the energy that reaches the sensor system (5:143). The MODIS data Dasgupta used has a 1 km GSD. This 1 km GSD is standard throughout much of the literature on remote sensing for fire danger as well as the available data products. MODIS data has the advantage of a high revisit rate. This makes the platform good at detecting changes from one day to the next, as well as providing opportunities to recollect if there is a bad collection (i.e. ground is obscured by cloud cover). Since this thesis is interested in what is happening in these WUIs, this shortcoming will be addressed with a different data source (further discussion in Chapter 3).

Closing

Addressing the problem of wildfires in the WUI for the military provides a perfect opportunity to showcase what how remote sensing and data fusion in a GIS can create a

meaningful decision support tool. This chapter explored the current state of practice for wildfire danger assessment. Current approaches and products are not designed to address the unique problem set of wildfire risk in the WUI, where, coming in to contact with human development, the consequences of fire are arguably greater. Because they are not designed to assess these areas, the data and methods used produce products at a scale incapable of making that assessment. In an effort to identify, quantify, and monitor hot spots within the the WUI landscape, Dasgupta's physics-based FSI will be employed against Landsat 8 data. While, as argued, the new view afforded by the 30 m GSD give the required access to the WUI, it also presents a validation challenge.

Dasgupta validated his FSI results against the published FPI for the same time period with 83% correlation (5:144). With this, he determined the FSI was a valid fire risk estimator (5:144). This validation worked because both products have a 1 km spatial resolution. The FPI is not available at the 30 m resolution. Calculating it is not possible because it relies on historical RG values, and they do not yet exist for the Landsat 8 bandpasses. Similarly, no other published fire assessment products are available at this resolution. The initial results must, therefore, be evaluated another way.

Topography plays an important role in wildfire behavior (see Appendix A). Generally, south and southwest slope receive more sunlight resulting in higher temperatures, lower humidity, and lower fuel moisture (38:2A.3). Historical evidence shows these slopes "are the most critical in terms of [the] start and spread of wildland fires" (38:2A.3). Conversely, north facing slopes see less fire activity with lower temperatures, higher humidity, and higher fuel moistures (38:2A.4). I will look for these patterns in the data as an initial assessment of the results.

Calculating the FSI at a new resolution, while novel, does little to make the data useful to decision makers. By using a GIS and including additional data for assessment and orientation, the data becomes dynamic for the user. A GIS, as discussed, also provides a platform to store and share the data, as well as reuse the products for further data fusion activities. The following chapter details the methodology.

III. Methodology

The intent of this thesis is to demonstrate the utility of fusing remote sensing data in a geographic information system (GIS) to assist in providing information for decision making. To accomplish this, a method for designing a decision making tool based on the Fire Susceptibility Index (FSI), introduced in the previous chapter, is presented to address the issue of wildfire in the wilderness urban interface (WUI) on and around military installations. The effort's scope is bounded with respect to a full risk assessment using Haddow's Hazard Risk Assessment process. Mountain Home Air Force Base (AFB) in Idaho was chosen as the area to apply the method, and effort was executed in Esri's ArcGIS suite. Figure 9, below, provide an overall look at this fusion process. As shown, the activities are not necessarily linear, and the datasets are often reused for multiple purposes. This chapter walks through calculating the FSI, along with tuning the regression equation, and the data used to do so. It then continues through further fusion work in interpreting and displaying the data, along with the additional data sets used.

Hazard Risk Assessment

In Chapter 2, the four steps of hazard risk management were introduced. The scope for the entire four-step activity is too broad. Having identified wildfire in the WUI as the hazard, step one, this thesis focuses on providing a tool for understanding the likelihood of the hazard as part of step two, the risk assessment. Understanding the consequences of the wildfire hazard, completing a combined hazard risk analysis, and

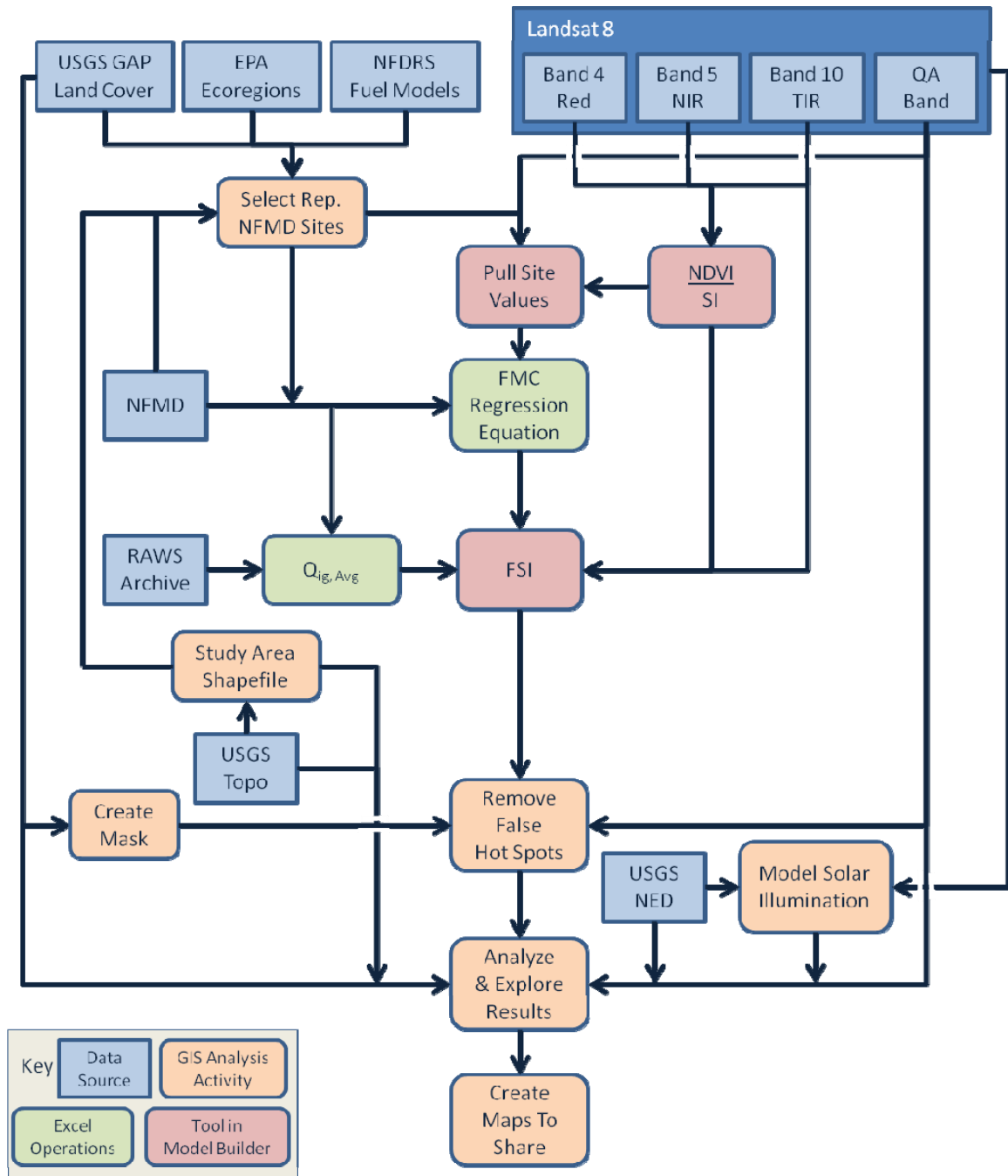


Figure 9: Fusion Methodology Flow Diagram

reducing the risk through hazard risk treatment are beyond the scope and focus of this effort.

The Geographic Information System

Esri's suite of products, including ArcMap and ArcCatalog, were used for this thesis. Numerous help files, training modules, white papers, and blogs are available online to help understand or execute the methodology presented here. All of the data was kept in a series of folders and imported to File Geodatabases with set environments. All coordinate system transformations were done on the fly by Esri. Calculations were executed in specialized tools built specifically for this work in Model Builder; they are described individually in later subsections. The tools are designed to string the outputs of one simple operation (addition, for example) to the inputs of another simple operation. Parameters can be designated as changeable or user supplied values while running the tool from a GUI. Creating, debugging, and using specialized tools allowed for error-free batch processing of datasets.

Choosing an Application Area

Theoretically, any DoD WUI location could be chosen to apply this method. The scope of applying it to the entire US would be too much for a single thesis as FSI regression equations would need to be built and tailored as fuel conditions changed. Needed data for Alaska and Hawaii were not guaranteed to exist, so the investigation was limited to the conterminous states. Looking back at the 2012 and 2013 fire seasons, one fire stood out: The Kinyon Road Fire around and on Mountain Home AFB. What was so outstanding about this fire was its sheer size and rate of spread. In less than a week, it consumed just under 235,000 acres (367 square miles) (16). In comparison, it

was nearly as large as 2013's Rim Fire in California. Not untypical of the threats seen over the past few years, the fire ignited naturally from lightning, starting off base, and spreading on. After investigating available information for the area, I determined it would suit well for this data fusion demonstration.

Home to the 366th Fighter Wing, Mountain Home AFB is a true WUI, located about 55 miles from Boise, Idaho and cited in a high desert near the Sawtooth Mountains and Snake River (See Figures 10 and 11, respectively). The base is split into three sections: the main base, a compact 10 square miles with an airfield and the usual support; the Saylor Creek Bombing Range to the southeast, an undeveloped 160 square miles; and the Small Arms Range Annex just north of the main base (an undeveloped 5 square miles). Off base, there are some irrigated farm fields, but the rest is wildland and ranch land. The view in Figure 12 shows many of the other federally and state managed lands, including: Morley Nelson Snake River Birds of Prey National Conservation Area (the vast unlabeled tracts south and west of base), Bruneau Dunes State Park, Boise National Forest, Sawtooth National Forest, Duck Valley Indian Reservation, Humboldt-Toiyabe National Forest, and numerous Wilderness Study Areas, each many times the size of Mountain Home AFB. Shapefiles were created by hand of the base perimeter from USGS Topo (introduced later) (visible later in Figure 18). Along with 25 and 100 km buffers, they were used to quickly identify the base's location and give a sense of scale while working with the data.



Figure 10: “OVER IDAHO -- A six-ship formation of F-15C Eagle and F-15E Strike Eagles fly over the Sawtooth Mountains of Idaho Oct. 13. (U.S. Air Force photo by Master Sgt. Kevin J. Gruenwald)” #2 (4)



Figure 11: “OVER IDAHO -- A six-ship formation of F-15C Eagle and F-15E Strike Eagles fly over the Sawtooth Mountains of Idaho Oct. 13. (U.S. Air Force photo by Master Sgt. Kevin J. Gruenwald)” #3 (4)

Mountain Home AFB Study Area Federal Lands

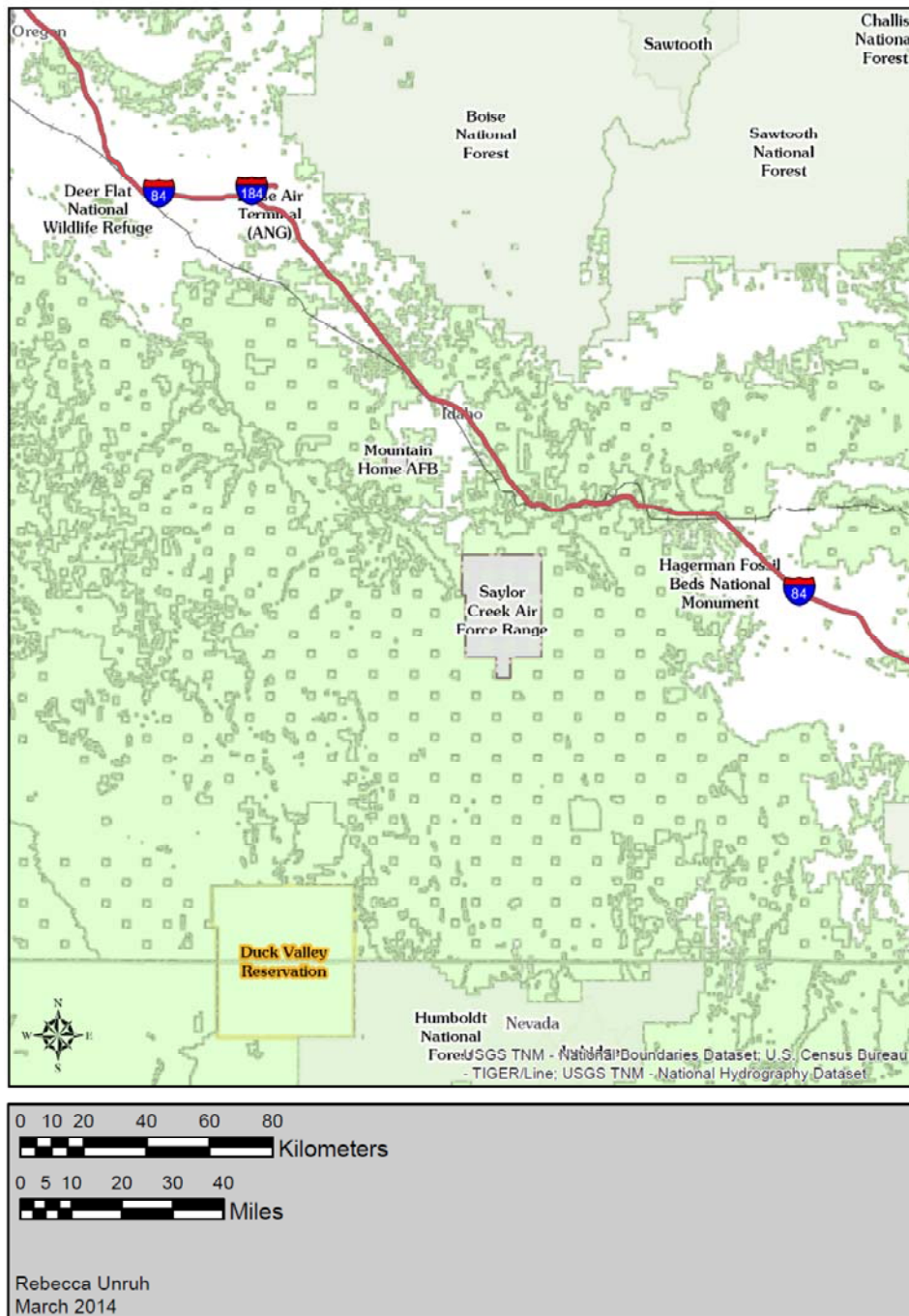


Figure 12: Federal Lands Surrounding Mountain Home AFB (39)

Calculating the Fire Susceptibility Index

Dasgupta's FSI was introduced in Chapter 2. To calculate an FSI, remote sensing data is needed to approximate the energy to ignition, Q_{ig} , including red and near-infrared (NIR) reflectances, and thermal infrared (TIR) emissions to approximate for fuel temperature. Before a Q_{ig} can be calculated, a regression equation must be built to correlate fuel moisture content (FMC) to the calculations from remote sensing data requiring additional FMC values from the study area. Finally, calculating the FSI also requires calculating an average Q_{ig} , requiring area average FMC and surface temperatures, again, approximating fuel temperatures. Following is a discussion of the different data types, how they were chosen, and how they were applied.

Landsat 8

Dasgupta realized the 1 km ground spatial distance (GSD) from MODIS was insufficient for use near urban areas. Because that is my area of interest, a remote sensor with a much finer GSD was necessary. Landsat, with its 30 m GSD and “cartographic accuracy of 12 m or better (including compensation for terrain effects),” is a logical choice (40). However, it is not used as often in the wildfire literature, especially where highly temporal change detection is required. Much of this boils down to data availability.

The Landsat revisit rate is much longer than the NOAA polar satellites. With only two passes a month, if one or both of the days are clouded out, an unacceptably long time can pass between data availability. Much about wildfire is highly temporal; the high revisit rate of AVHRR or MODIS sensors allow for daily and weekly condition

monitoring. Second, there was a data quality or usability issue until Landsat 8 was launched in February 2013. Before that, Landsat 5, launched in 1984, was operational, but aging and has since been decommissioned as of June 2013. Landsat 7, launched in 1999, suffered a permanent hardware failure in 2003, leaving striped data products missing 22% of the area coverage (41).

That said, Landsat data has generated many products, and some, like land cover or burn scar analysis, are used by the wildfire science community. Landsat 8 with regular, reliable data holds promise for wildfire behavior, risk assessment, as well as post-fire analysis and recovery. This past August and September, it made a debut and the news supporting Incident Command fighting the Rim Fire with fuel condition and burn scar assessments. For this effort, once hot spots have been identified, periodic updates will suffice; existing tools, such as National Fire Danger Rating System (NFDRS), can be used to stay apprised of daily fire danger conditions and changes for the general region.

The Landsat data was limited to Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). Not only does Landsat 7 have the striping issue, the sensors are different (Landsat 7 flies the Enhanced Thematic Mapper Plus (ETM+), collecting in slightly different bands. This means a regression curve built for relating NDVI/ST to FMC for one sensor is not necessarily applicable to the other without considerable study. A table below, Table 2, compares the available bands of Landsat 8 to the MODIS products as used by Dasgupta. Though different, when considering the spectral reflectance profile of green vegetation versus dry vegetation, both sensors should perform equally as well. Considering atmospheric transmission, the Landsat 8 red and IR

bands are collecting where the transmission is maybe 1-2% higher, otherwise, they are quite comparable in range of responsivity and Landsat is usable for calculating an FSI.

Table 2: MODIS – Landsat 8 Sensor Band & Resolution Comparison (42;43)

	MODIS	Landsat 8
Red	1 km	30 m
	Band 1	Band 4
	0.62 - 0.67 μm	0.64-0.67 μm
NIR	1 km	30 m
	Band 2	Band 5
	0.84 - 0.88 μm	0.85-.088 μm
TIR/Land Surface Temperature	1 km	100 m resampled at 30 m
	Band 31	TIRS 1/Band 10
	10.78-11.28 μm	10.60-11.19 μm
	Band 32	TIRS 2/Band 11
	11.77-12.27 μm	11.50-12.51 μm

Landsat data is available for free download off both the USGS Earth Explorer and the USGS Global Visualization Viewer (GLOVIS). An account with user name and password is required for download; both access points link to the same account. (See Appendix B under USGS Earth Explorer and USGS Global Visualization Viewer.) Because the data sizes are large (each set is roughly 1 GB, compressed), using bulk download was preferred.

Landsat imagery is downloaded as a set by date and World Reference System (WRS) (WRS-2 for Landsat 8) path and row. Each set includes Bands 1-11 as individual GeoTIFFs, a Quality Assessment (QA) GeoTIFF, and metadata in a text file. Identifying and previewing the data is more user-friendly in Earth Explorer because it can be viewed

along with more complete orientation data, allowing easy assessment of path and row coverage. Alternately, shapefiles of the WRS-2 path and row boundaries can be downloaded (see Appendix B under USGS Landsat Missions). Mountain Home AFB falls in path 41, row 30. Fifteen days from 11 April to 21 November, were pulled as the fire season generally falls within this time period.

Each band's GeoTIFF is a raster of digital numbers (DN), quantized and calibrated. The metadata contains the values needed to convert each band into the required reflectance or radiance. USGS has posted guides to understanding the data format and accomplishing the conversion (see Appendix B under USGS - Landsat Missions). The QA band is used to identify pixels with clouds, snow, missing data, etc. This data is stored as 16-bit coded binary. The USGS also explains how to decode these pixels in a guide. Let's take a closer look at each product and how it was employed.

Bands 4 and 5: Red and NIR

Working with Bands 4 and 5 is straight forward. They were each converted from DNs to solar angle corrected top of the atmosphere (TOA) reflectances (ρ_{TOA}). The variables for Equations 7 and 8 are contained in the metadata for each set. Together, they were used to compute the Normalized Difference Vegetation Index (NDVI).

First, an initial ρ_{TOA} , ρ_{TOA}' , is calculated for each band with rescaling coefficients in Equation 7 (44):

$$\rho_{TOA}' = M_p DN + A_p \tag{7}$$

Where

- M_p Band-specific Multiplicative Rescaling Factor (REFLECTANCE_MULT_BAND_X)
- A_p Band-specific Additive Rescaling Factor (REFLECTANCE_ADD_BAND_X)

Then, it is roughly corrected for solar angle for a final ρ_{TOA} with Equation 8 (44):

$$\rho_{TOA} = \rho'_{TOA} \div \sin(\theta_{SE}) = \rho_{TOA}' \div \cos(\theta_{SZ}) \quad (8)$$

Where

θ_{SE} Local Sun Elevation Angle
(SUN_ELEVATION)

θ_{SZ} Local Solar Zenith Angle

Where

$$\theta_{SZ} = 90^\circ - \theta_{SE}$$

As USGS reports, “for more accurate reflectance calculations, per pixel solar angles could be used instead of the scene center solar angle, but per pixel solar zenith angles are not currently provided with the Landsat 8 products” (44).

Finally, the NDVI is calculated with the Equation 1, introduced in Chapter 2, and reformatted here:

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1a)$$

Where

NIR Band 5 ρ_{TOA}

RED Band 4 ρ_{TOA}

All the calculations were done in Esri’s ArcMap. To streamline the calculations, I built several tools. Figure 13 shows the workflow for Band 4 in Model Builder. Basic addition, multiplication, and division tools from Esri’s toolkit (depicted with the hammer in the square) were enlisted to execute the calculations with the requisite inputs. Figure 14 shows the resulting GUI. NDVI was calculated along with NDVI/ST, covered in the next subsection.

The results of the tools were verified with spot checking (checking single pixels at random) using the Identify tool in ArcMap and running the inputs through hand calculations to check the outputs.

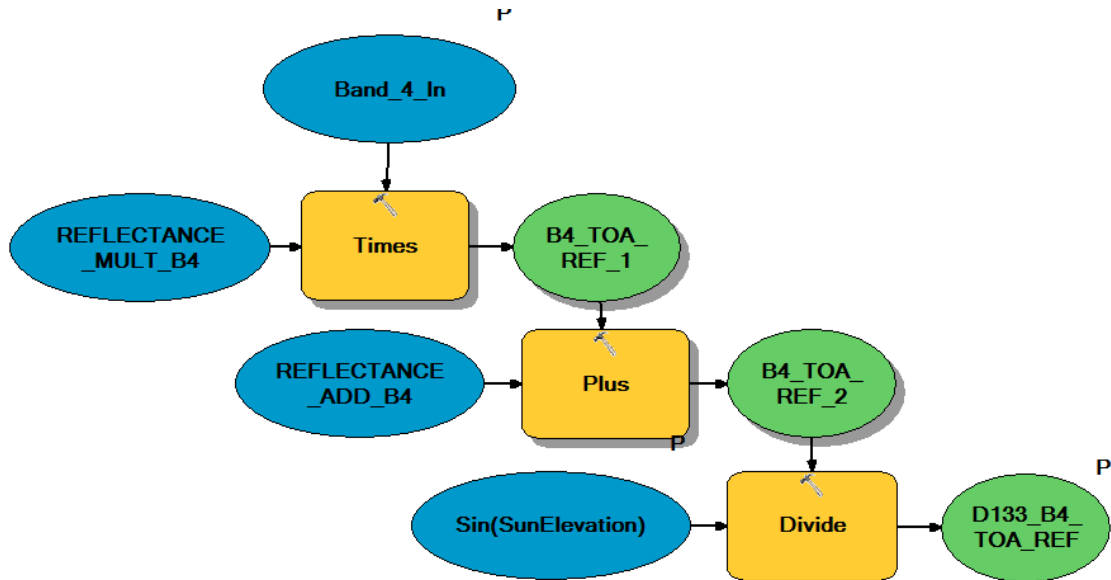


Figure 13: Band 4 TOA Reflectance Tool Model Builder Workflow

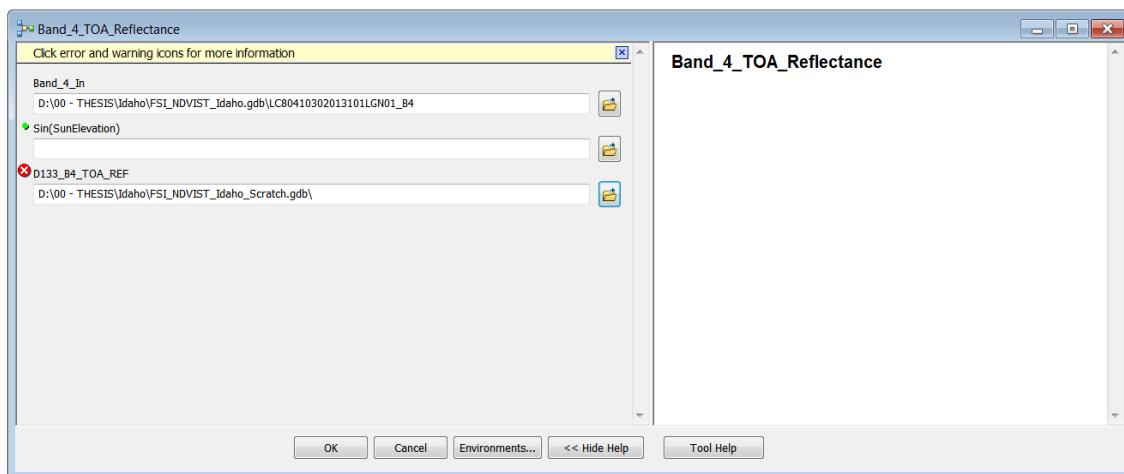


Figure 14: Band 4 TOA Reflectance Tool GUI

Bands 10 and 11: Thermal Infrared

Surface temperature (ST) is used both in the FSI calculation and in calculating FMC through NDVI/ST. Turning Bands 10 and 11 into TOA brightness temperatures, $T_{B,TOA}$, is also straight forward. From there, getting a surface temperature is not. Landsat

8 TIRS was designed with two TIR bands instead of the one its predecessors had. This enables the use of a split-window algorithm for determining ST. This is how it is done with MODIS and AVHRR.

The split-window algorithm uses two adjacent TIR bands between 10 and 12 μm eliminating the need for obtaining or assuming associated atmospheric information and modeling its effects on electromagnetic radiation to obtain a ST from $T_{B,TOA}$. Behind the algorithm are thousands of computational simulations executing a radiative transfer code, such as MODTRAN, varying atmospheric temperature, atmospheric column water vapor, surface temperature, and land surface emissivities. Proper execution of most of these algorithms requires well known spectral response functions for the sensor system, knowledge of the atmospheric water vapor content, a roughly estimated near-surface air temperature, and well characterized emissivities for land cover types over your sensor's bands. The coefficients are unique to a sensor, and have not been published for Landsat 8. The development takes time, and more importantly, the sensors are still undergoing calibration. On 3 February 2014, all Landsat 8 data was pulled from internet download for recalibration. The split window algorithm development cannot be completed until the sensor has finished calibration.

Developing this algorithm is outside the scope of this thesis. Looking back at Dasgupta's discussion of the FSI, he showed that the FSI was more susceptible to changes in FMC than fuel temperature (what ST is standing in for) (5:141). A temperature change of +30 K only resulted in a change of +6 on the FSI. Spot checks of temperature in the 30 June Band 10 frame taken at 1128 local time show brightness temperatures around 325 K ($\sim 125^\circ\text{F}$) just east of the Saylor Creek Range where the Twin

Buttes RAWS station is located. Twin Buttes reported temperatures of 88° F at 1055 and 96° F at 1155 that morning, giving a rough surface temperature during the flyover of 92° F (~306 K) (45). This +19 K difference and resulting FSI difference, about +4, does not introduce gross error into the decision making tool, and if anything errs on the side of caution, identifying potential hot spots for further investigation. Spot checks showed Band 11 $T_{B,TOA}$ were roughly 1 K higher than Band 10 in cloud free areas. Reviewing the posted calibration notices with USGS, Band 11 data pre-recalibration has twice the temperature error and twice the uncertainty of Band 10 (46). Using weather data from another source is potentially possible, but doing so introduces other sources of error. The obvious choices, such as AVHRR, collect on a 1 km GSD, a scale not commensurate with the red and NIR from Landsat. There is also likely to be some time difference in collection, which can alter the results. With the limitations and this analysis, Band 10 $T_{B,TOA}$ was chosen to serve as a stand-in for ST until a split-window algorithm and recalibrated data can be incorporated into the tool.

Calculating $T_{B,TOA}$ is done in two steps; the variables for Equations 9 and 10 are contained in the metadata for each set. First, an TOA radiance, L_{TOA} , is calculated from the DN with rescaling coefficients in Equation 9 (44):

$$L_{TOA} = M_L DN + A_L \quad (9)$$

Where

M_L	Band-specific Multiplicative Rescaling Factor (RADIANCE_MULT_BAND_X)
A_L	Band-specific Additive Rescaling Factor (RADIANCE_ADD_BAND_X)

Next, L_{TOA} , is converted into $T_{B,TOA}$ with Equation 10 (44):

$$T_{B,TOA} = \frac{K_2}{\ln\left(\frac{K_1}{L_{TOA}} + 1\right)} \quad (10)$$

Where

K_1 and K_2 Constants in the metadata file

All the calculations, including NDVI/ST, were again done in Esri's ArcMap with specially built tools. Figure 15 shows the workflow for Band 10 in Model Builder.

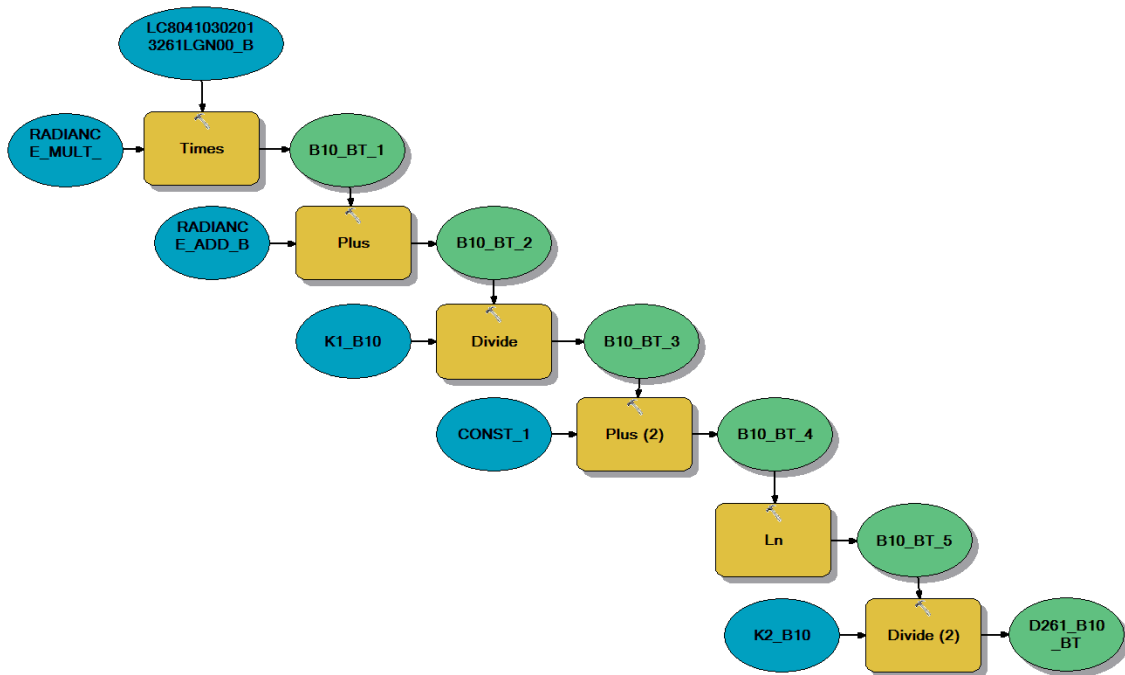


Figure 15: Band 10 TOA Brightness Temperature Tool Model Builder Workflow

The results of the tools were verified with spot checking inputs and outputs with hand calculations. The boarder space surrounding the images (see Figure 16) along with the fact the OLI and TIRS sensors do not completely overlap created issues trying to display the data because the large extremes created by divide by relative near-zero

(actually 1) errors in calculating NDVI/ST. To combat this, shapefiles were created by hand for each dataset that encompassed the footprint contained both sensors. The data inside was extracted, and the remainder was thrown away. This added step is shown in the NDVI_ST_2 tool workflow shown in Figure 17.

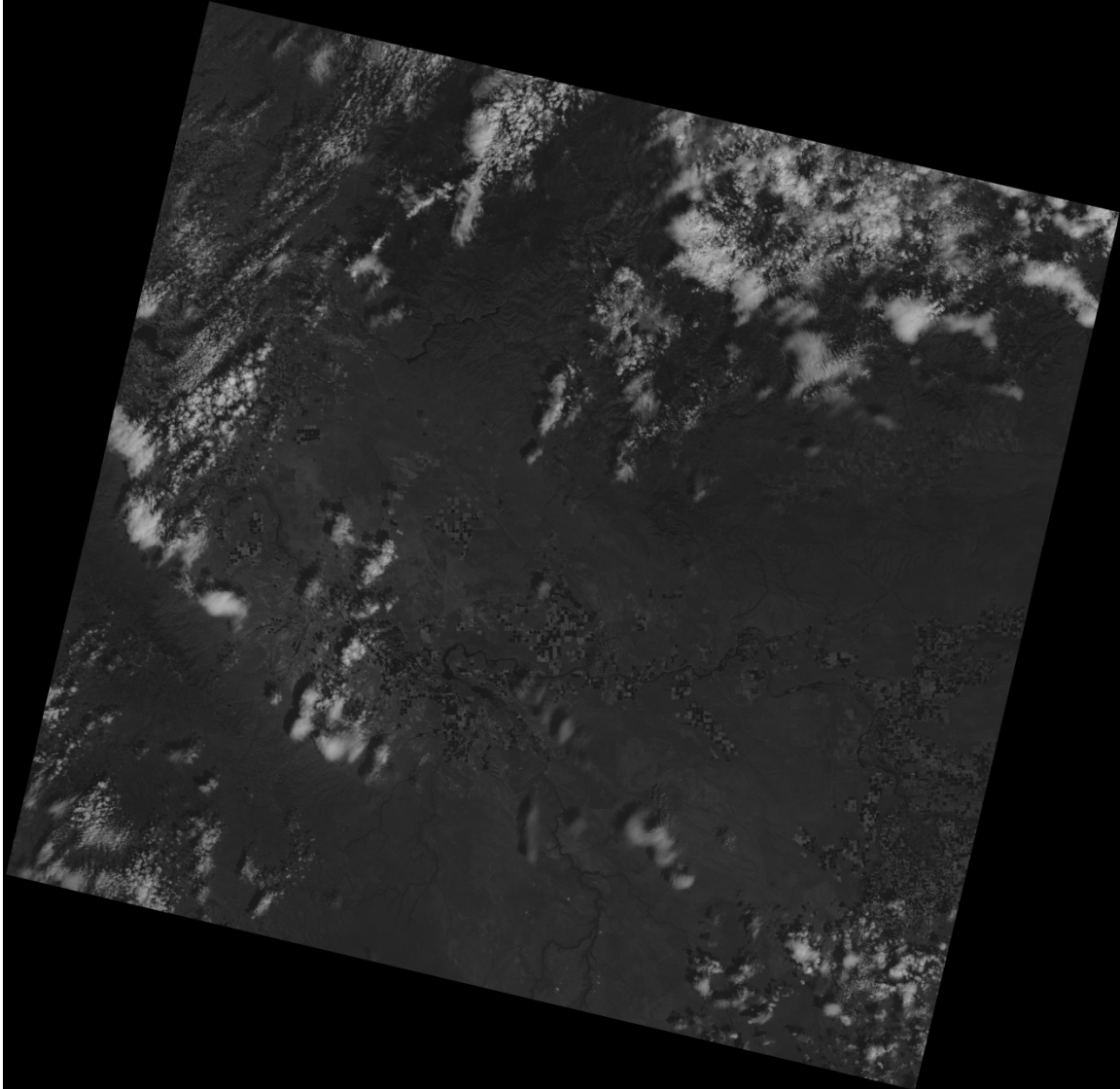


Figure 16: Image Boarder Around Landsat 8 (Day 133, Band 4) (47)

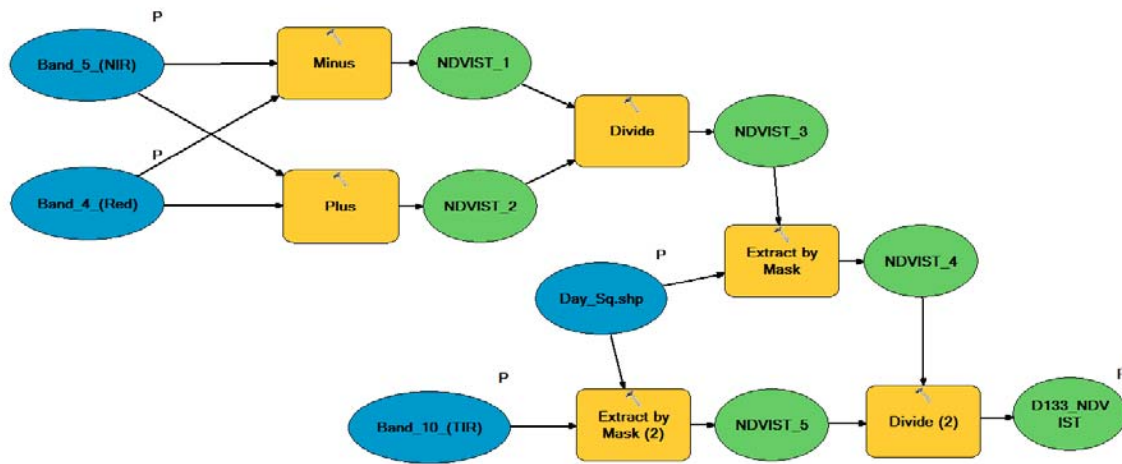


Figure 17: NDVI_ST_2 Tool Workflow

Quality Assessment Band

Since the QA Band is part of the Landsat dataset, it will be discussed here. The QA Band stores information in 16-bit coded binary. The decoding is documented by USGS and not explained here (see Appendix B under USGS – Landsat Missions). The QA Band was used to screen the use of FMC collection sites for building the NDVI/ST to FMC regression equation, eliminating those under the cover of clouds or falling on a snowfield. In reality, none of the sites fell in a snowfield during the fire season. Later, the band was used to place snowfields and clouds back in the scene to assist in data assessment. (More on the process in a following section.)

The National Fuel Moisture Database

Having ground truth fuel moistures is key to correlating remote sensing data to ground conditions. Dasgupta used the NFDRS calculated live woody FMC from the RAWS stations available through the Georgia Forestry Commission. While a nice setup

for the state of Georgia, similar data is not readily accessible for the rest of the country. To access all the NFDRS calculated values from RAWS data for most stations requires a point of contact (not published) for each station data is needed from. From there, station managers either must pull the data from the archive, or, for those that have a Weather Information Management System (WIMS) account, the station manager can grant access. The very knowledgeable folks at the WIMS helpdesk agreed that this would not be particularly easy. Since calculated FMC was difficult to come by, a deposit of actual field measurements was sought and found.

The National Fuel Moisture Database (NFMD) was launched in 2006 (some of the data is even older) as a deposit of field measured live and dead FMC from sites across the country for anyone who needed access to such information (48). The NFMD is accessed through Wildland Fire Assessment System (WFAS) (link in Appendix B). All the data is arranged by collection site (a latitude and longitude), specimen sample (plant species or dead fuel class), and collection date. Many of the sample sites are linked to RAWS stations, and with the often regular twice monthly collections, it is possible some of these are the same field samples used to recalibrate the NFDRS calculations.

Using actual field measured FMC is arguably better than those calculated by NFDRS because the field measurements not only reflect fire weather and drought, but also other environmental stressors, such as beetle kill in Colorado from the Mountain Pine Beetle.

The Idaho has 57 collection sites in the database. The locations of each site are placed on a Google map, making it easy to identify where they are located. Sites in the vicinity of (say 200 km, not measured) Mountain Home AFB were investigated. The

samples collected as well as the site's NFDRS fuel model, if reported, was noted. The latitude and longitudes of those with data from 2013 were collected and placed into an Excel file. The coordinates were converted from degrees-minutes-seconds to decimal degrees. From there, they were imported to ArcMap as a shapefile using the Add XY Data function, a tool in ArcMap. Since no metadata was found, it was assumed GPS was used to collect the site coordinates and they were assigned the WGS 1984 datum.

Once the tabular data became spatial data, it was evaluated for suitability for creating the NDVI/ST to FMC regression equation for Mountain Home AFB. Three other data sets were considered: the NFDRS Fuel Model Map, the USGS Gap Analysis Program (GAP) Land Cover, and the Environmental Protection Agency (EPA) ecoregion. These data sets are discussed further in a following subsection. The conditions on base and off were evaluated and compared to the conditions at the NFMD collection sites. Naturally, the selection and regression equation tuning process was iterative and somewhat subjective, as will be discussed shortly. Four sites found suitable were not included as they fell outside of the path 41 row 30 footprint and the scenes were never pulled. Sufficient data points were found, however, in the 15 scenes pulled to build the regression equation. A list of the suitable sites, including the four not used, are below in Table 3.

Tuning the FSI: Fuel Models, Land Cover, and Ecoregions

Dasgupta created a single regression equation relating FMC to NDVI/ST for the entire state of Georgia with an R^2 value of 0.54 (5:143). He did this considering the land surface types at the RAWS sites and found them to be representative of the whole state of

Table 3: NFMD Collection Sites Suitable for Mountain Home AFB

NFMD Collection Sites Suitable for Mountain Home AFB	
Sites Used	
	Balanced Rock
	Blackstone
	Hammett
	Three Island
	Triangle
Sites Unused	
	Notch Butte
	Rye Grass Flat
	Shoshone Basin
	Three Creek

Georgia (5:142). Comparing his FSI results to the published Fire Potential Index (FPI), this method seemed to work with an 83% correlation (5:144). However, in the mountain west, the variety and rate of change of ecoregions, ground cover, and fuel models is amazing. The mountains, and the associated changes in elevation, play a large role in this phenomenon. The larger cartographic scale (smaller GSD) of the Landsat data can only amplify the differences. Not all collection sites within the state or a certain radius of Mountain Home are suitable. Comparing Figure 1 in Chapter 1 to Figures 10 and 11 shown here in Chapter 3, all taken on the same day in October, the change in the landscape between the area immediately surrounding the base and the nearby Sawtooth Mountains is obvious. To ascertain the applicability of collected FMC data to the base and surround, a way to characterize the base and discern one collection site from another was necessary. This same information was then used to selectively tune the FMC regression equation. The three products considered and discussed here are: the NFDRS

Fuel Model Map, the USGS GAP Land Cover classification data, and the EPA ecoregion classification data.

NFDRS Fuel Model Map

The NFDRS Fuel Model Map is the result of an effort in the late 1990s to map the conterminous United States and assign each 1 km by 1 km area a fuel model (49). A feature in-feature out (FEI-FEO) data fusion product itself, a combination of land cover data, Omernick ecoregions, and selective field assessment was used to create the map (49). The map was designed for large area use in conjunction with NFDRS analysis, not local work on large-scale maps (49). A GeoTIFF version of the map is stored as a raster of 1 km by 1 km cells and is among the many products available for download on the WFAS website (see Appendix B under USGS Wildland Fire Assessment System). While the legend for the fuel models was updated in 2010, it is unclear from documentation that the data in the map was also reviewed and updated at the same time. The potential age of the data along with the fact it was never intended for use on large-scale, local analysis are concerns that limit the use of this data in this thesis. While an indicator of possible ground conditions, it is not suitable to use alone.

USGS National Gap Analysis Program Land Cover

The USGS GAP land cover dataset provides vegetation and land cover information on a 30 m by 30 m grid. A data in-feature out (DAI-FEO) fusion product itself, it is a compilation of regional GAP work and the LANDFIRE program created from Landsat data from 1999 to 2001 and the 1999 National Elevation Dataset (NED) (50). In July 2011, the USGS released version 2 of the GAP land cover data set after

updating and crosswalking version 1 to the five highest levels of the National Vegetation Classification (NVC) System (50). Information on the NVC System, its supporting documentation, and classification descriptions is available on its website (see Appendix BB under US National Vegetation Classification). The GAP dataset along with its metadata is available for download from the USGS GAP website (see Appendix BB under USGS National Gap Analysis Program). The dataset is also available for immediate import to maps from Esri on ArcGIS Online for those with access. With the 30 m by 30 m grid, the data is perhaps the most detailed of the three, however, the metadata warns, “these data are not intended to be used at scales larger than 1:100,000” (perhaps only discernible to the nearest 100m when printed out on paper with the naked eye) (50). The GAP data also identify land covered with water, urban development, introduced vegetation, and agriculture activity. Assessing the FSI for the paved airfield, for example, is of no value. This data will enable the creation of masks, eliminating these areas from the assessment.

EPA Ecoregion

The EPA Ecoregion designations are based on James M. Omernick’s 1987 framework and subsequent improvements. Shapefiles are available for download from the EPA’s Western Ecology Division (see Appendix B under US EPA: Western Ecology Division). I downloaded the Level IV ecoregions, and because of the naming convention, Levels I-III can be derived. The data is created by digitizing ecoregions mapped on 1:250,000 topographic maps into shapefiles for GIS use and is not recommended for use

below a 1:24,000 scale (51). The data was last updated and published 16 April 2013 from 2011 digitization of field data (51).

Tuning and Calculating the FSI

The beautiful thing about working in a GIS system is the ability to quickly and visually evaluate and explore spatial information. Loading each, the land cover classifications, the fuel model, and the ecoregions into ArcGIS, it was easy to see that the locations of transitions in one data set were similar to those in the next in many cases. It was also a way of understanding how to best use each data set. The fuel model, while perhaps useful for generally classifying an area around a point, in transition areas is perhaps less reliable as it artificially assigns a fuel model to a large prescribed area in its underlying 1 km by 1 km raster. There is also its age to consider. The EPA ecoregions and GAP land cover both have a finer level of detail making them more suited to larger scale analysis, and the data is more recent.

Mountain Home AFB and surround are dominated by NFDRS Fuel Model T, sagebrush and grass. Some of it is Model L, western perennial grass, and the remainder is agriculture (no fuel model). Figure 18 is a map of Mountain Home AFB and the surrounding NFDRS Fuel Model.

The land cover is widely dominated by D040, Western North American Cool Semi-Desert Scrub and Grassland, interlaced with D301, Introduced and Semi-Natural Vegetation. Again, Herbaceous Agriculture, D101, is identified, along with D200, Developed and Urban, and D500, Open Water. There are also very small pockets of D055, North American Cool Semi-Desert Cliff, Scree, and Rock Vegetation; and D022,

Mountain Home AFB Study Area NFDRS Fuel Models

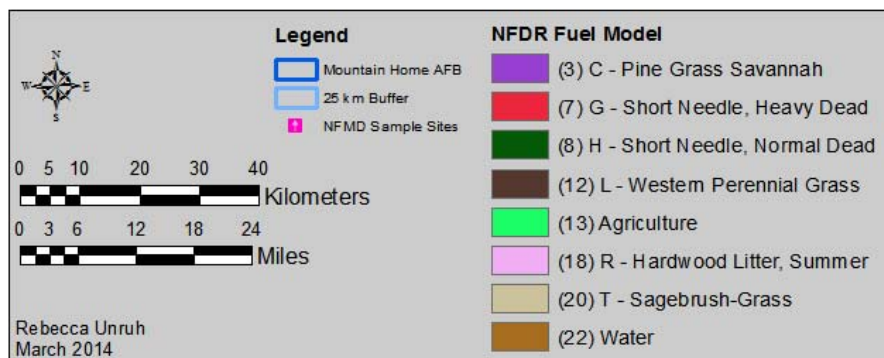
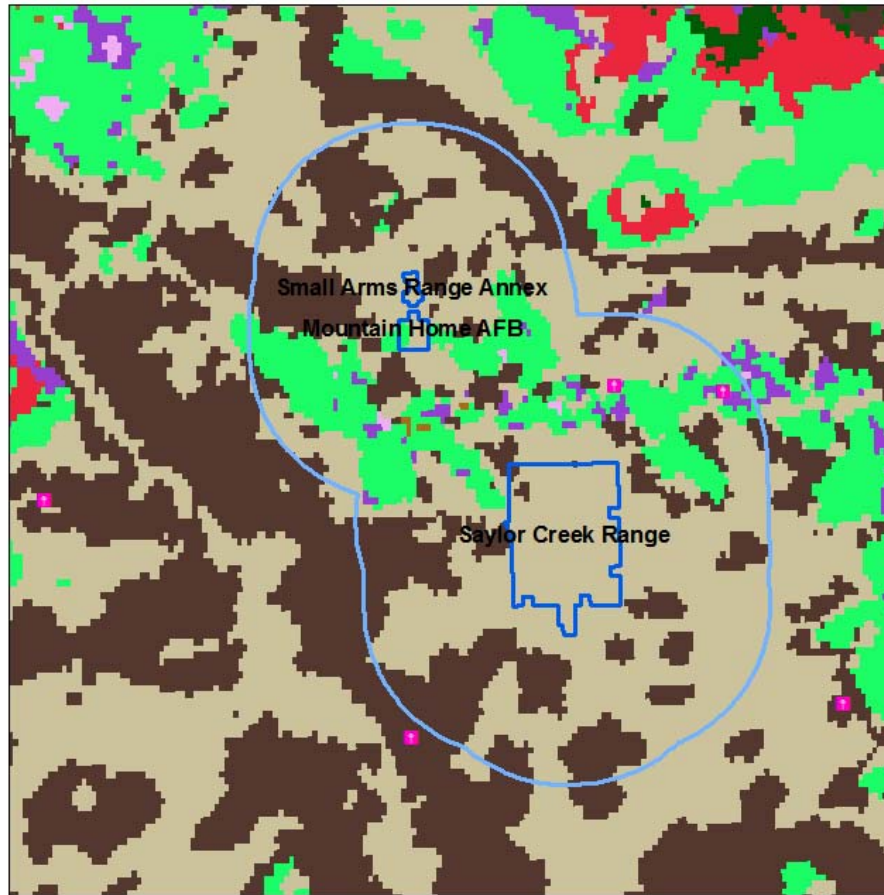


Figure 18 – NFDRS Fuel Model - Mountain Home AFB (49)

Western North American Grassland and Shrubland. There are even pockets of D036, North American Western Interior Brackish Marsh; and D012, Western North American Flooded & Swamp Forest, mostly along the Snake River. Figure 19 is a map of Mountain Home AFB and the surrounding land cover.

Mountain Home AFB actually sits in two ecoregions. The main base and small arms annex are in 12h, the Mountain Home Uplands, on the north side of the Snake River. On the south side of the river, Saylor Creek Range falls in a transition zone, containing 12h, 80a, a Dissected High Lava Plateau, and a small bit of 12j, Unwooded Alkaline Foothills. Northeast of the base, the mountains are their own series of Level 4 ecoregions; the Level 3 is 16, the Idaho Batholith. Figure 20 is a map of Mountain Home AFB and the surrounding ecoregions.

Despite falling on the boarder of two ecoregions, the similarities seen in both the fuel model and GAP land cover, suggest a single regression equation will suffice. The equation was developed from the five sites in Table 3 (also identified in the maps on Figures 18, 19, and 20) which had the same characteristics as the base and surrounding high desert. Collection sites that were not representative of both sides of the river (i.e. specialized in multiple minor characteristics without displaying the dominant characteristics of the high desert) were eliminated from consideration, as were all sites in the mountains. Most collection sites only collected FMC content for one plant species, a woody shrub: Wyoming Big Sagebrush.

Actual FMC measurements were pulled from the NFMD for the sites, and the specimen collection dates were correlated with Landsat 8 flyover dates. Three cases were considered for building a regression equation: specimen collections day of the flyover

Mountain Home AFB Study Area USGS GAP Land Cover

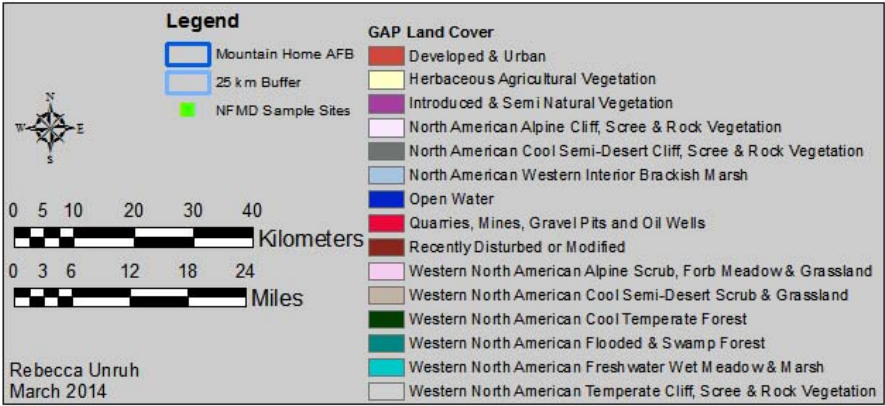
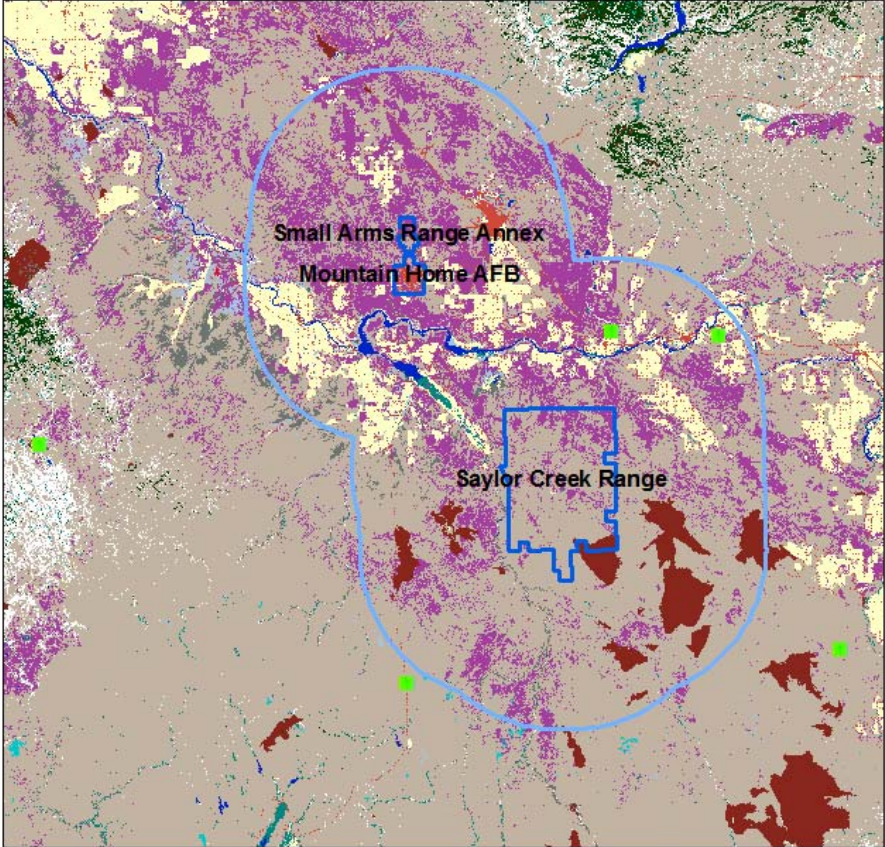


Figure 19 – USGS GAP Land Cover - Mountain Home AFB (52)

Mountain Home AFB Study Area EPA Ecoregions

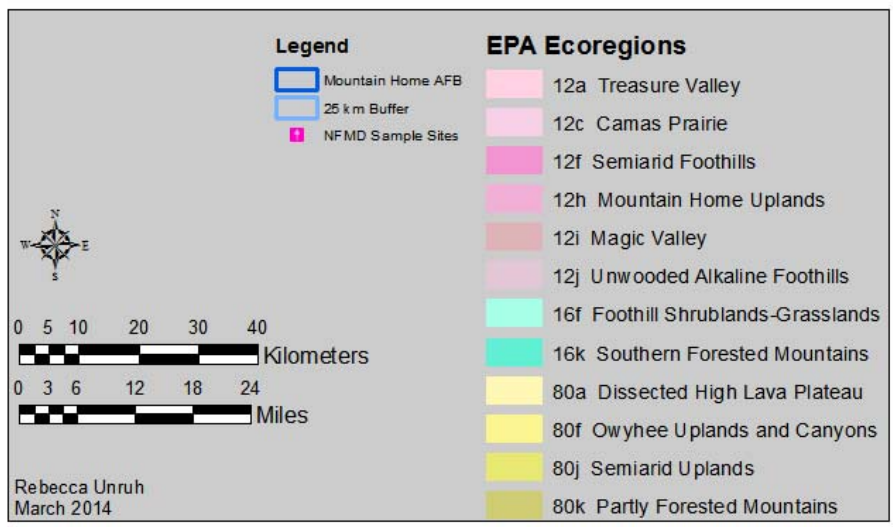
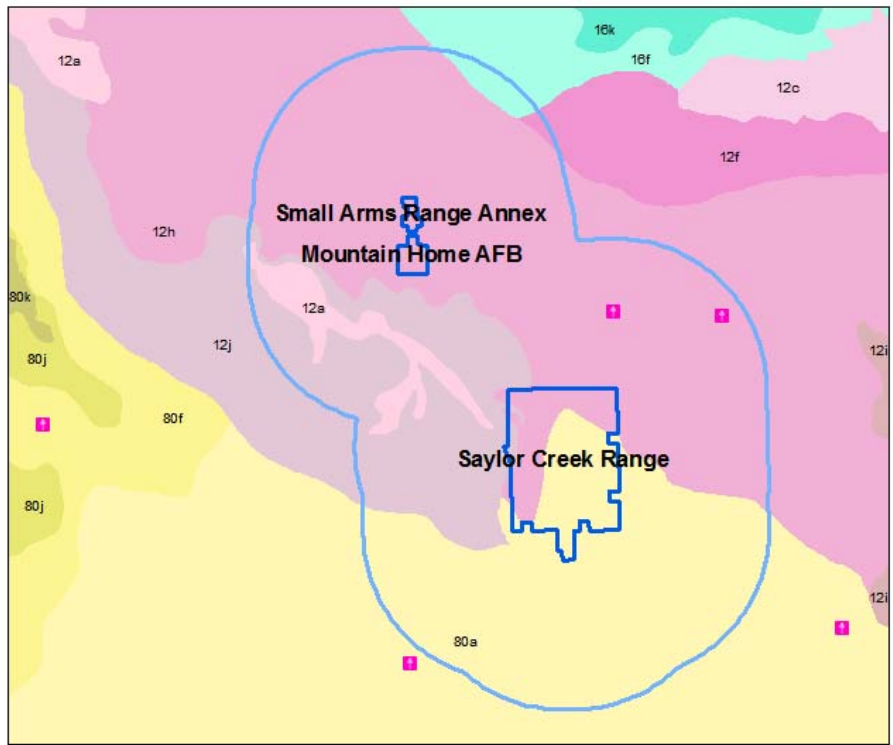


Figure 20 – EPA Ecoregions - Mountain Home AFB (53)

(1-day window), specimen collections day of and plus or minus a day of the flyover (3-day window), and specimen collections day of and plus or minus two days of the flyover (5-day window).

For sites with days identified as correlating, values for NDVI/ST needed to be pulled from the calculated frames in ArcMap. To account for uncertainty in exact location of collection and simultaneously miss nearby road surfaces, an average was calculated for all cells inside 60 m radius buffers around each collection site and multiplied by 1000 due to their small size. After the inflation, the values generally fell between 0.1 and 1.6. A 100 m buffer was tried, but was found to contain cells with land covers classified as Urban Development, the roads accessing the sites. Sites that eliminated Urban Development land covers saw averages decrease in the hundredths place. Those without only saw changes in the thousandths or ten-thousandths places. A tool with a GUI was built in Model Builder and checked to facilitate the data pull, SS_Avg_NDVIST_Pull. Also in ArcMap, the QA band was used to eliminate specimen site-collection date combinations under cloud cover. This was done by visual inspection.

The field measured FMC values were married with the calculated NDVI/ST in Excel to create the regression equation. The 1-day window case could not be used; it had only one data point. The individual data point itself was an outlier on the scatter plot. After further inspection was found to lie in the shadow of a cloud and was eliminated. The 5-day window case was not ideal due to the temporal nature of FMC, but was considered in the event there was insufficient data or poor correlation from the 3-day case. Not surprisingly, it showed more variation, and its regression curve ($FMC=209(NDVI/ST)-27$) only had an R^2 value of .58. The 3-day case was exceptional.

With an R^2 value of .82, it outperformed Dasgupta's effort. The scatter plot is shown below in Figure 21.

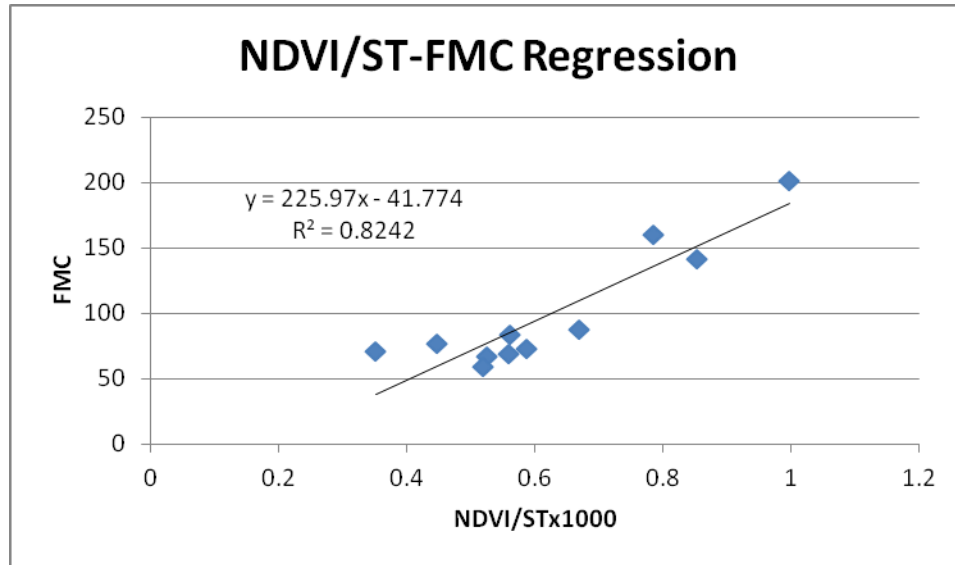


Figure 21: Scatter Plot of NDVI/ST and NFMD FMC

Equation 11 is the regression equation used to estimate an FMC for the FSI. A Model Builder tool, ID_FMC, was created in ArcMap to test this sub-routine before it was added to the final FSI calculation.

$$FMC = \frac{NDVI}{ST} \cdot 1000 \cdot 225.97 - 41.774 \quad (11)$$

To calculate an FSI for any given day, two items were still needed, an area average FMC and average ST. This year was particularly hot and dry in Idaho; the average FMC from the five sites was only 97. The average of all FMC recoded for the 5 collection sites, going as far back as 2004 was calculated at 115. This value was used for computing $Q_{ig,avg}$. After reviewing historic weather data from NOAA for the area, the

average temperature was set at 300 K (~80° F). These values yielded a $Q_{ig,avg}$ of 2738.794 KJ/Kg using Equation 3 from Chapter 2.

Finally, using Equation 6 from Chapter 2, FSI was calculated. The calculation was coded into a tool, FSI_IDAHO, with Model Builder; parameters were chosen for the GUI. Again, to debug the tool, the Band 10 BT was extracted with the day's shapefile, reducing the data to where the two Landsat 8 sensors overlapped. The final output was validated by spot checking cells with hand calculations. Figure 22 shows the Model Builder workflow for calculating the FSI.

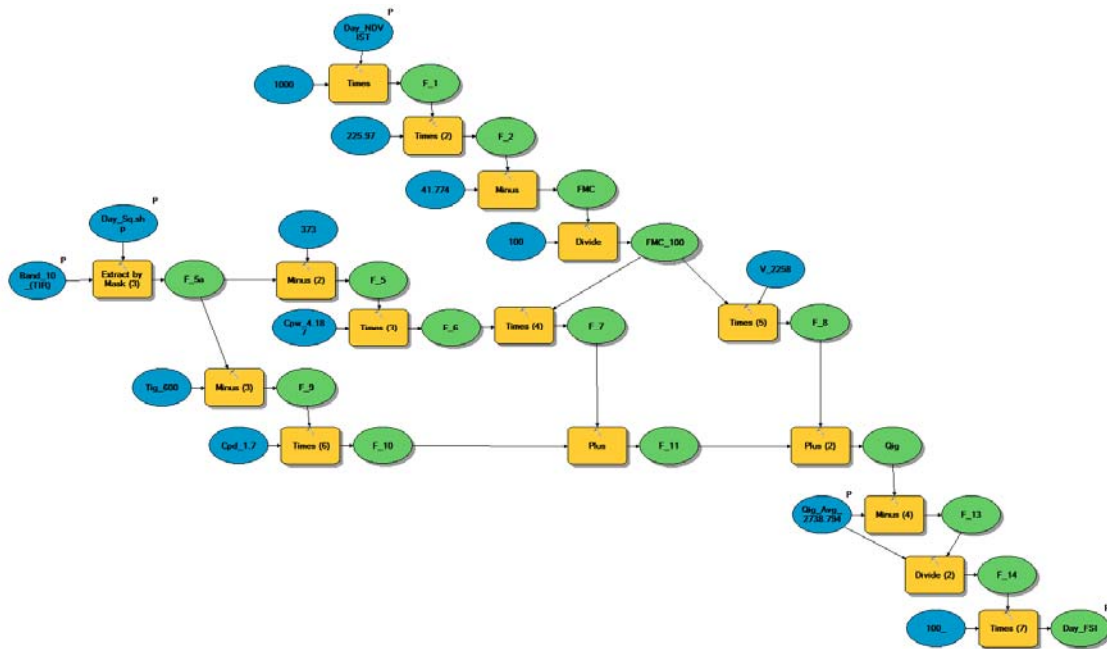


Figure 22: FSI_IDAHO Tool Model Builder Workflow

Below, Figure 23, shows the raw FSI calculated for path 41, row 30 on 30 May 2013. Like all the intermediate calculations, the FSI values are held in a 32-bit floating point raster. The values stretched on grayscale from low in black to high in white. Immediately noticeable are the dark irrigated farm fields, the brilliant white of the Snake

River, and the very light colored airfield on Mountain Home. As discussed in Chapter 2, the art of display is where data becomes usable information. The next section addresses what is needed to help evaluate the results and make this data interpretable and a useful for decision making.

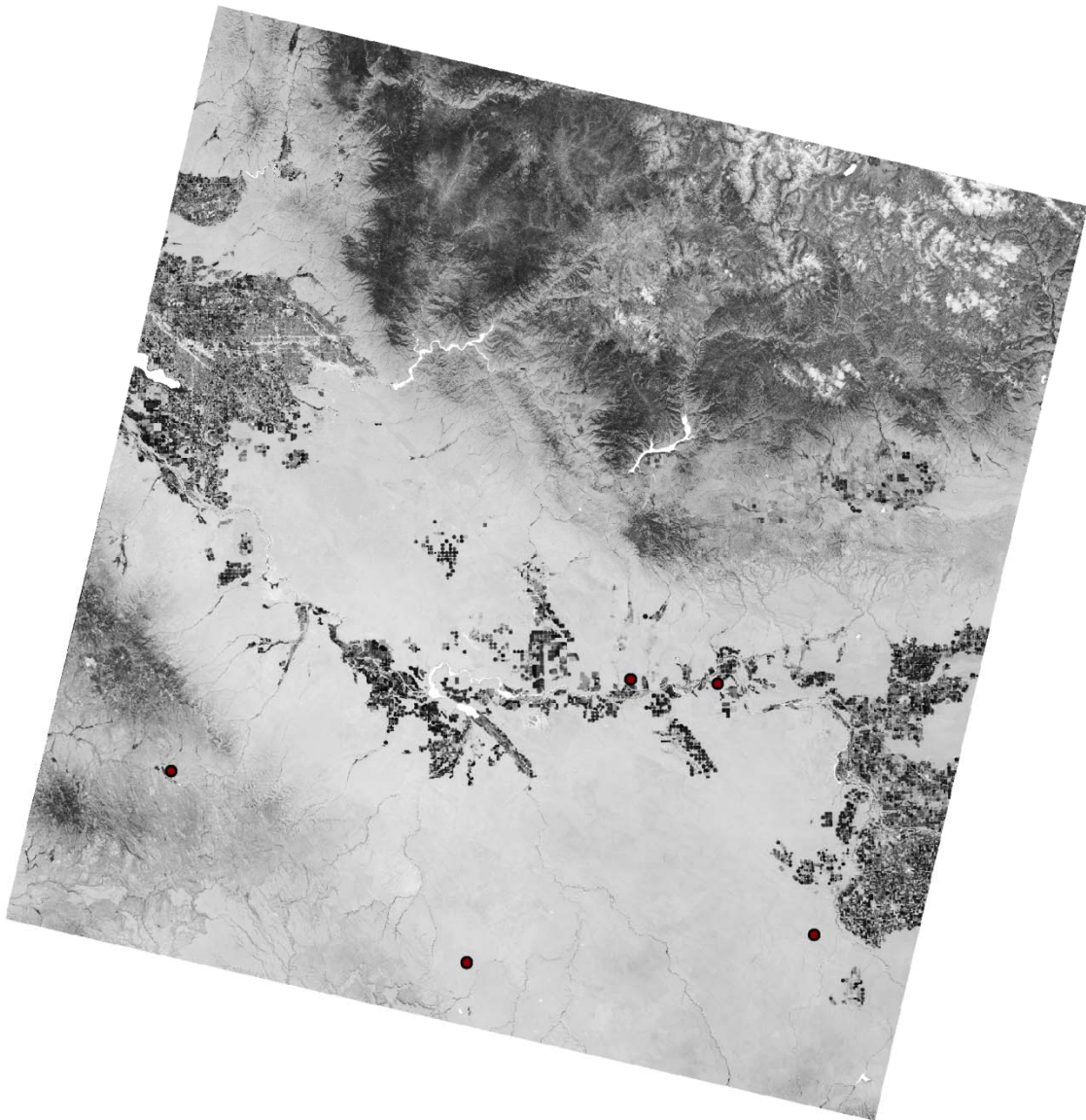


Figure 23: FSI Path 41, Row 30 on 30 May 2013 (47)

Interpreting & Displaying the Data

Without contextual information, there is little about the image in Figure 23 giving clues to its content. Further work is required to interpret data, and display and share the fire susceptibility information. First, additional data are required beyond what has already been used to both orient the user in the data and interpret the results. Second, the display of the data and FSI results must be manipulated in a manner that makes them useful and easier to interpret, share, and use. Both the additional data and the art of display for interpretation are explored here.

Data for Assessment and Orientation

To this point, 6 datasets have been used to assess the region around Mountain Home AFB, build the regression equation, and calculate the FSI. Further data are needed to interpret those results. Elements from the National Map, in particular elevation data from the USGS National Elevation Dataset (NED) and US Topo, were also included. Not only helping evaluate and interpret the results, the layers also orient the analyst or user in the data. Here is a brief look at the two datasets.

Elevation: The National Elevation Dataset

The USGS publishes and maintains the NED. It is available for download through the National Map (see Appendix B under USGS – The National Map). The NED, a data in-data out (DAI-DAO) fusion product, is comprised of many sources including old land surveys, space based radar, and airborne lidar. As new updates or higher resolution data become available, it is incorporated. The NED is updated twice a month (54). The NED comes as two products, the elevation raster and the metadata

shapefile. The rasterized NED data is available at several resolutions (1 arc second, 1/3 arc second, 1/9 arc second) for most of the United States and into Canada and Mexico. Because the NED is created from many data sources and seamlessly incorporated with different methods, as appropriate, individual locations can have unique metadata. For this reason, the metadata is stored as attributes in a shapefile. These attributes include: available resolutions, source, collection date, and more.

The NED serves two purposes: first, to orient the analyst and user in the landscape, and second, to assess the calculated FSI. Looking at the results in Chapter 4 will show that without being oriented in the landscape, understanding what FSI calculations are showing with respect to wildfire behavior is not possible. Because of topography's effect on fuel, it should be considered when assessing and interpreting fire susceptibility, especially at large cartographic scales. Moreover, because there is no other published 30 m wildfire risk assessment product with which to potentially validate the results in a similar manner to Dasgupta's use of the Fire Potential Index (FPI), we must return to wildfire behavior basics for validation.

Thirty-five 1° by 1° rasters were downloaded and stored in a separate File Geodatabase because of its large size (nearly 50 GB). The rasters were combined into a Mosaic using the Mosaic toolsets in ArcMap. To increase processing speed, a smaller raster was extracted from a hand-drawn shapefile roughly of the WRS-2 path 41, row 30 footprint.

The Basemap: US Topo

Most data is displayed over a basemap. This orients the user in the data with a map where they can find common areas with recognizable landmarks. USGS has a very extensive collection of orientation data available for download through The National Map, everything from state borders and water features to current Congressional District boundaries and active rail lines is available. I chose to use US Topo maps. Topographic maps are visualized at multiple levels of detail, 7.5 minute (1:24,000), 15 minute (1:62,500), 30 minute (1:100,000), and larger. The maps depict and label many useful features: boundaries, roads, buildings, contour lines, and much more. On the base, the topographic maps show the airfield, hospital, base housing, and even the locations of bombing targets out on the ranges. It is worth noting that the location information for some commercial roads is copyrighted. However, there is no limit to the reproduction and use of the data provided the copy right markings are retained. While using a basemap has been introduced here while discussing interpreting and visualizing the data, in truth, the US Topo basemap was used from the beginning; it was indispensable for orientation on an otherwise blank page.

Analysis and Display Techniques for Exploration, Interpretation, and Sharing

Given an NDVI/ST to FMC regression equation, a GIS system is not necessary to calculate the FSI. What the GIS system provides is not only a platform for performing calculations on spatial data. The system also provides a way to store data in layers and a platform to dynamically explore and visualize the data as is shown in Chapter 4. A few

of the many techniques are presented here, including working with color and transparency, removing and replacing data, using elevation data and its derivatives, and crating maps.

Color & Transparency

A logical color palate to display FSI data runs from green, representing a low FSI, to red, representing a high FSI. By making the layer partially transparent, layers below can be seen. This can be helpful when looking at some of the other display elements, including the USGS Topo basemap and hillshade.

Stretched Display and Classified Symbology

The stretched symbology assigns one of 255 color values to the raster based on the highest and lowest value in the raster (zero is reserved for no data cells). This assignment can be customized but is sometimes difficult. Stretched symbology is wonderful for viewing changes on a large scale in a portion of the data if there is enough definition in the color value spread. However, over the entire scene, it can be difficult to interpret some types of data. This is true of the FSI data because FSI is an open scale. What areas are not of concern? What constitutes a hot spot? Also, the high and low FSI values will change from date to date, changing the assignment of color to a particular FSI value. Classifying the data can help with this.

To classify the data, the values are binned according to set breakpoints. There are many ways of classifying the numbers. Remembering FSI is a value giving the percent of normal an area is more or less susceptible to fire, initial break values were chosen to reflect common regular percentage breaks and then adjusted after data exploration to

reflect meaningful breaks. Eight classes were chosen. Shades of green were used for areas having less than average fire susceptibility; Shades of yellow and red for those having more than average fire susceptibility. Figure 24 compares the keys for symbolizing FSI in stretched and classified displays.

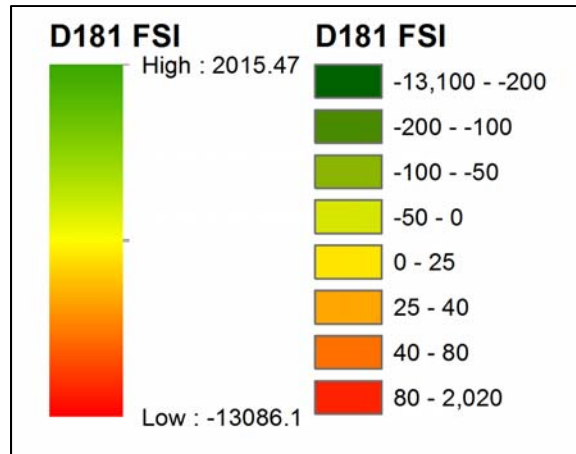


Figure 24: Stretched and Classified Symbology for FSI

Creating Masks: Removing Urban Development and Open Water

Another way to enhance FSI display is to cut out parts of the output that are not of concern. The two land covers chosen for removal were D200, Developed and Urban, and D500, Open Water. Referencing Figure 23, above, both elements look “hot”, having a high FSI. First, leaving these elements in the image, they appear as false positives that would require investigation. Second, removing them allows for other orientation layers be seen underneath. Adding a USGS Topo, rivers and lakes appear, as do roads, and large buildings if the data is not partially transparent.

The masks were created by using ArcMap's Set Null tool. Using a logic expression, this tool set any cell with the value of D200 or D500 to Null, or no value, and everything else was set to 100. Because the cells in the land cover layer do not co-register with the Landsat cells, they are only accurate above a 1:100,000 scale, and the interest is to remove false hot spots, the removed cells needed to be further trimmed back in ArcMap. To accomplish this, the mask raster was first turned into a shapefile using the Raster to Polygon tool. The resulting shapefile was trimmed back into a second shapefile using the Buffer tool, cutting a buffer of -30 m, the size of one cell. Finally, the FSI raster was extracted by the trimmed shapefile using the Extract by Mask tool in ArcMap.

Hillshade: Seeing Topography and Modeling Solar Illumination

One ArcMap tool makes this data come alive more than many of the others: Hillshade. Hillshade takes elevation information in the NED, positions an illumination source (here the sun), and colors space in light and shade based on its aspect. The default location has an azimuth of 315° and an altitude of 45°, placing the sun in northwest sky. When looking at a map, this is how the topography is normally displayed. In this manner hills and valleys are intuitive for most people to interpret. With this view, the classically dry south and southwest slopes can be identified.

By changing the azimuth and elevation values, the illumination source can be moved. Earlier this chapter, the effect of an area lying in shade resulted in an NDVI/ST-FMC pair being removed from creating the regression equation. Likewise, areas lying in shade because of topography can falsely flag as hot spots. The Landsat metadata contains the azimuth and elevation of the sun during the flyover. By modeling the

illumination conditions at the time of flyover, areas lying in sun and shade can be identified. From here, spots that appear hot but lying in shade can be potentially eliminated and hot spots in full sun can be potentially confirmed.

Adding Layers: Clouds, Snow, and Other Artifacts

The Landsat QA band flags cells containing clouds, snowfields, and other artifacts. By changing how each discrete binary number is symbolized, clouds and snowfields were placed back in the scene and the few no data pixels were likewise masked from the scene. Cells with clouds, snowfields, and artifacts were displayed in light shades of white, blue, grey, and cream. The remaining cells were left clear (or not symbolized). This is important for two reasons. First, the areas with clouds or snow the calculated FSI is really an FSI of the imaged clouds and snow and, like open water and developed urban areas, really means nothing because fuel is not being imaged. Second, the cloud layer casts a shadow on the ground, the effects of which have been discussed. Because of this, the clouds cannot be simply masked out in the same way open water and developed urban areas were. The results of this are shown in Chapter 4.

Creating Maps

In Chapter 2, the principal components of a map and importance of including them were introduced. Those elements were included in making maps to present the data and results, particularly the legend, scale, direction indicator. A template was created to make the maps uniform in appearance. These maps are seen in Chapter 4.

This section has introduced additional data used to give context to the FSI output as well as some of the display techniques used to assist in evaluating, exploring, and interpreting the data and finally sharing the information. We will see the effects of this in Chapter 4 while reviewing the results.

Summary

This chapter has presented a method for designing a decision making toolset based on the FSI with a regression equation that outperformed Dasgupta's earlier work. The Landsat 8 remote sensing data provides visibility in the landscape at a scale not seen in the art of the practice with fire danger rating, and makes it particularly applicable to WUI land management. Fused with other data, including data and features from other fusion efforts, the method demonstrates the illustrative power of a GIS as seen in the next chapter which explores the results.

IV. Results and Analysis

This chapter explores, analyses, and presents an initial subjective validation of the results of the methodology presented in the previous chapter. The Fire Susceptibility Index (FSI) of the entire scenes is considered, as well as elements within them.

Comparisons between the dates are also made. Overall, despite the fact Landsat 8 data has not finished calibration and top of the atmosphere brightness temperatures were used as a stand-in for surface temperatures, the FSI calculations performed remarkably well.

In addition to investigating how the FSI performed, the utility of a Geographic Information System (GIS) is showcased. As mentioned in Chapter 3, a GIS was not necessarily needed to perform the FSI calculation. However, it has been instrumental to exploring, analyzing, and sharing the data.

Performance of the Fire Susceptibility Index

The FSI performed remarkably well. Recall from Chapters 2 and 3, the FSI is an open index “measure[ing] the normalized percentage deviation of energy required for ignition than the average case” (5:141). The average case was set for the high desert around Mountain Home AFB. Negative values indicate lower fire risk, positive values higher fire risk.

Figure 25, below, is a map of the 14 June FSI. Excepting the irrigated fields and the Bruneau Valley (the green area extending from the Strike Reservoir off the Snake

River), after having removed open water and urban development, most of the FSI values fall between -100 and +100. This was true for all the dates.

It is important to remember that the regression equation to compute the fuel moisture content (FMC) was generally tuned for Western North American Cool Semi-Desert Scrub and Grassland, interlaced with the Introduced and Semi-Natural Vegetation because it covers the majority of the land both on and just off Mountain Home AFB. Agriculture fields, the Bruneau Valley, and Bruneau Dunes State Park (the mostly red area off the northwest corner of Saylor Creek Range) do not have that land cover or the associated fuel model, neither do the Sawtooth Mountains (just on the northeast part of the map), so the FSI values here are not necessarily comparable to the majority of the surrounding wildland. There was no data to build regression equations for these areas (agriculture fields, Bruneau Valley, sand dunes). That said, they truly have higher (agriculture fields and Bruneau Valley) and lower (sand dunes) Normalized Difference Vegetation Index (NDVI) values, giving them the respective FSI values. What this means is while those areas should not be directly compared to the land to which the regression was tuned without further investigation, changes can be monitored in those areas over time. None of these areas appeared particularly concerning. The Bruneau Valley “stayed green” throughout the season, and the state park is covered with sparsely vegetated sand dunes and scree cliffs, making it more difficult for wildfire to spread in that area.

Without a GIS, making that assessment would have been tedious if not difficult. Land cover, fuel model, and topographic maps are quickly toggled on and off, allowing the user to superimpose the FSI raster and quickly realize those particular extremes were

Mountain Home Air Force Base Fire Susceptibility 14 June 2013

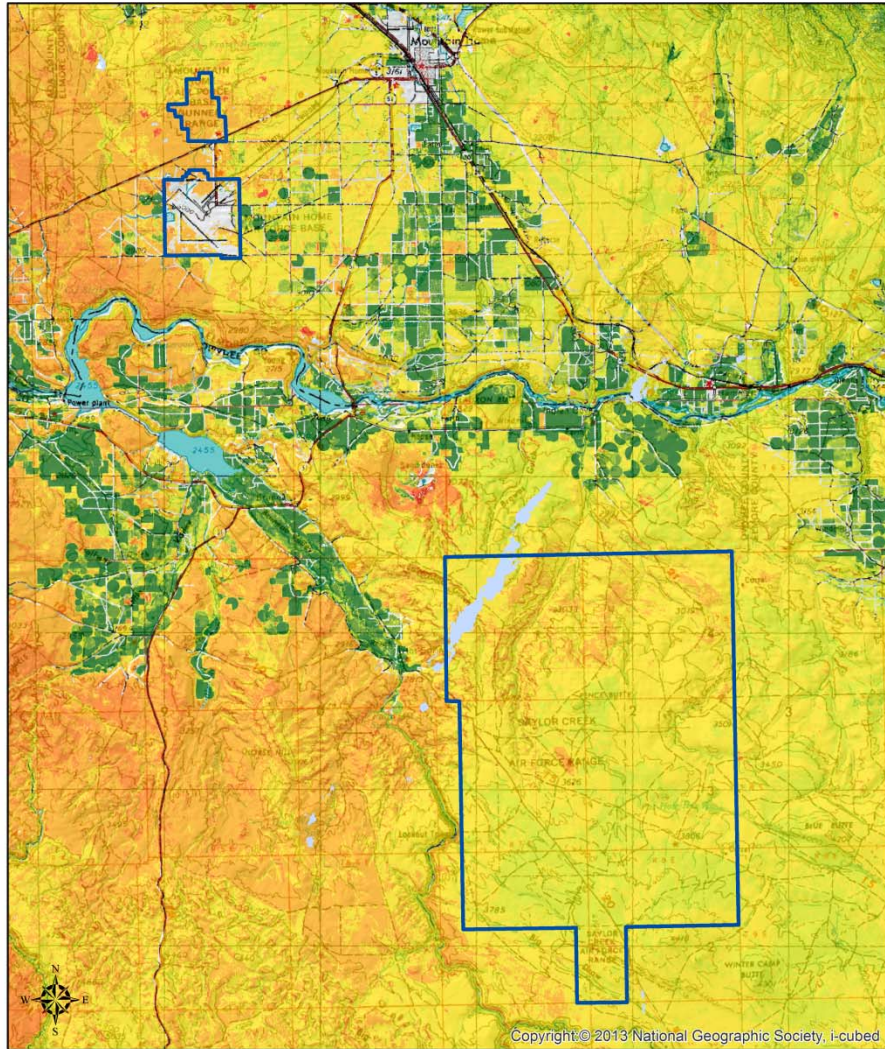


Figure 25: Mountain Home AFB FSI – 14 June 2013

outside the bounds of the regression equation. (Several figures, including Figure 25, show the FSI over the Topo; land cover and fuel models with the FSI do not show well statically, and should be viewed dynamically in a GIS.) In the metadata, descriptions of the land covers, especially for Bruneau Dunes State Park as it appears as a hot spot, make qualitatively assessing the area nearly instantaneous. Thinking back to Dasarathy's classification of data fusion, while not a technique requiring calculations from the user (the GIS still must render the data geospatially), this is an example of features in-decision out (FEI-DEO) fusion. Features of an area were stored in multiple data sets, accessed, fused visually and thoughtfully by the user, and a decision was made on how to regard FSI outputs for that area (ignore the sand dunes area, for example).

To evaluate how the FSI calculations performed in the areas where it was intended to be employed, the techniques outlined in Chapter 3 were used. In the next section both the techniques and results of the FSI calculations are explored, including a comparison to outputs from the National Fire danger Rating System (NFDRS).

Data Exploration, Analysis, and Display

This section discusses what was found when applying the analysis and display techniques discussed in Chapter 3, including the performance of the FSI calculations. Finally, after seeing the results of the analysis and display techniques, there is further reflection on how these techniques relate to data fusion and demonstrate the utility of conducting that fusion a GIS.

Searching for Hot Spots: Stretched and Classified Symbology

Part of assessing wildfire risk in the wilderness urban interface (WUI) is locating high risk areas so they can be monitored and or addressed. This is true of any decision support tool: identify areas of concern for further assessment and action. As stated in Chapter 3, using a classified symbology of the FSI, rather than a stretch symbology, facilitates quick identification and location of high risk areas. The stark difference is shown in the map below, Figure 26. The classified frame on top allows for quick comparison from one 30 m area to another. The stretch in contrast, makes it very difficult to locate the hot spots from the sea of yellow-orange. In the next subsection, the classified symbology will also enable change detection over time.

From a data fusion perspective, this seemingly simple change in symbology is actually quite interesting. Dasarathy has two categories of classification that take data in: data in-data out (DAI-DAO) and data in-features out (DAI-FEO). The input variables to the FSI algorithm are supplied by raw remote sensing data. However, it can be argued that changing the display changes the output level. Keeping the stretched display, you only have a data level product. Applying a classified display, however, gives each area a characteristic, making it a feature level output. The characteristic assigned is a relative level of risk; an area in red is of higher risk than the same area would be if it were classified yellow. To identify only high-risk areas, low-risk classifications could be symbolized as transparent (see method of displaying clouds and artifacts in Chapter 3) (not illustrated). Even more interesting, the underlying calculated FSI data is still in the layer; using the Identify tool in ArcMap will retrieve the actual FSI value, and the raster of values can be used for further calculations and fusion activities. A GIS is quite

powerful in this way, retaining low level data, but raising the level of output in a way that translates raw remote sensing data straight into feature information. Not only does a GIS do fusion on multiple levels, it brings data closer to usable information for decision support.

Hillshade: Seeing Topography and Modeling Solar Illumination

Elevation information and an understanding of wildfire behavior validated the initial results seen with the FSI. In Figure 27, below, two map frames are used to analyze an area just on and just off the Saylor Creek Range. In the top frame, the FSI is layered over the USGS Topo. It is apparent that the hot spots sit on south and southwest facing slopes. In the bottom frame, solar illumination at the time of flyover is modeled and lying under the FSI. None of the hot spots lie in full shade which could signal a false hot spot; in contrast, the western spot, just off the range, is sitting in full sun. From understanding wildfire behavior, it is expected those south facing slopes could be dryer, taking the brunt of the sun's rays. They should also be monitored as they could become even drier with hot, dry, sunny weather.

Changing focus to the light green areas along the northern edge in the center of the frames, the opposite phenomenon is found. The vegetation in the shallow north-facing drainages appear less susceptible than average to reaching pre-ignition. Again, understanding wildfire behavior, it is expected FMC on those north facing slopes could be higher. Here, there is less solar stress, and with the terrain feature, the vegetation in the drainage benefit from the runoff from above. The existence of these light green areas, along with others not illustrated here, further validate the initial results.

Mountain Home Air Force Base Fire Susceptibility 14 June 2013

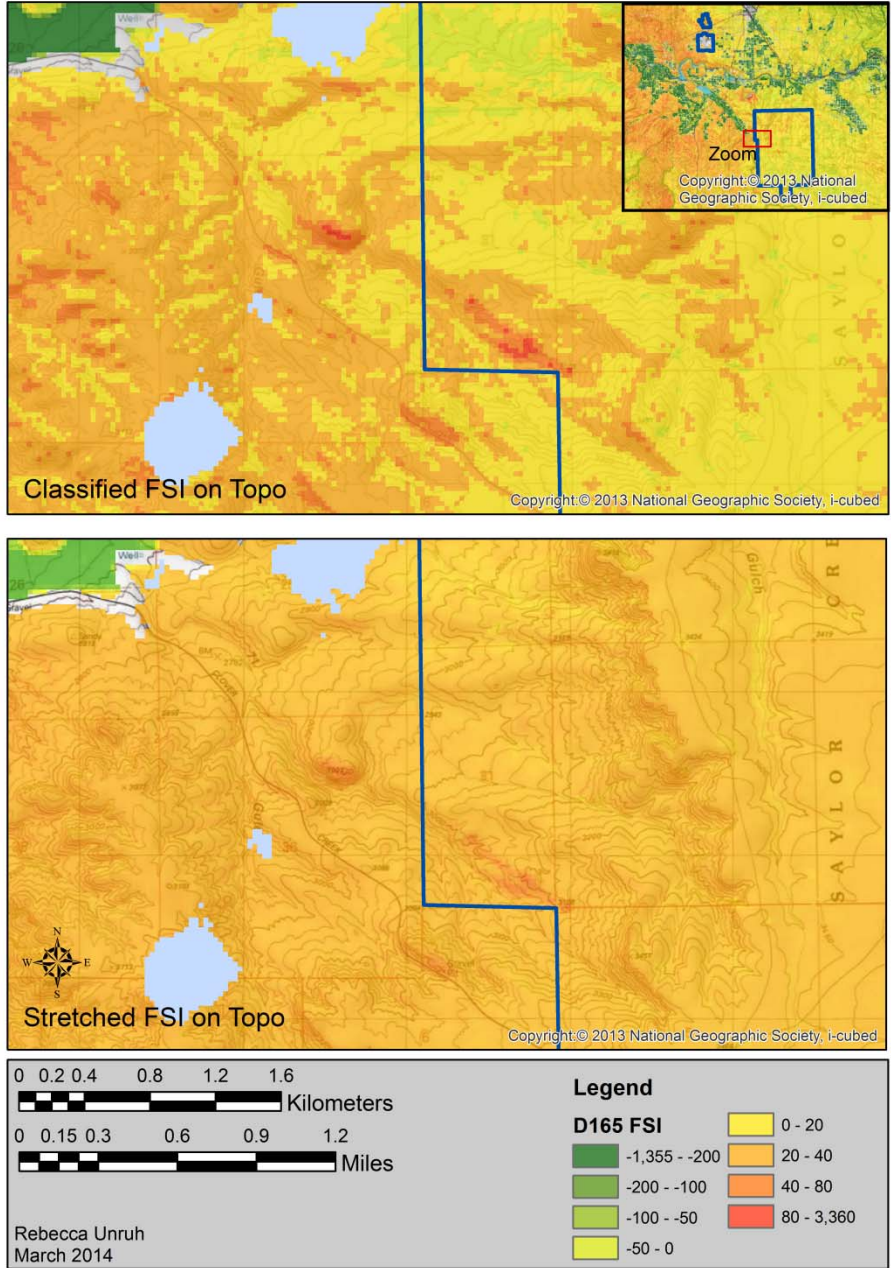


Figure 26: Comparing Classified and Stretched Symbology

Mountain Home Air Force Base Fire Susceptibility 14 June 2013

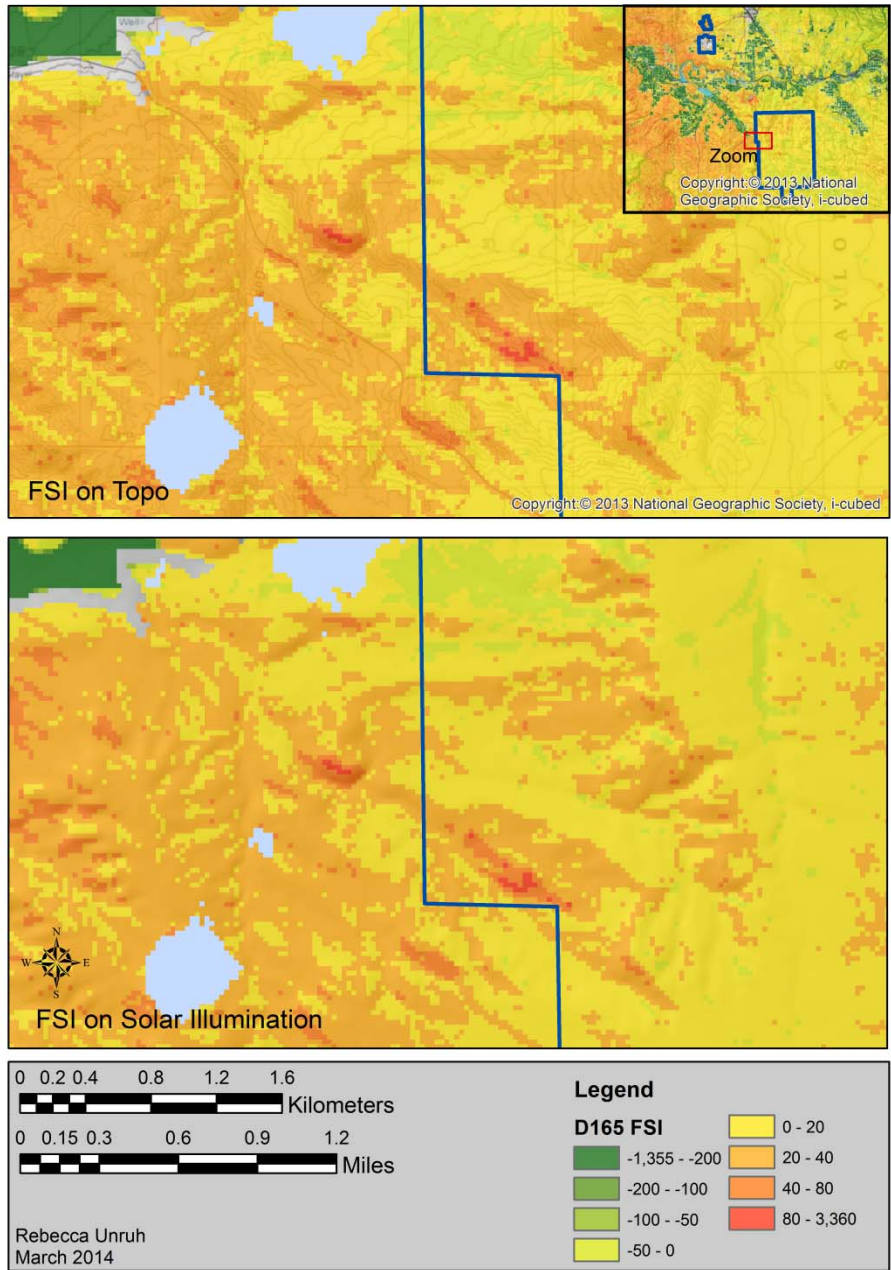


Figure 27: Using Elevation Data to Analyze FSI

The ability for a GIS to quickly model elevation and solar illumination is another reason a GIS is such a powerful data fusion platform. The FSI data alone is somewhat unremarkable. Being able to give context to an area with terrain information and illuminate collection conditions gives the calculated FSI real meaning. A user goes from locating a hot spot and referencing it by a pixel with a particular row and column address to actually knowing where on the earth's surface a hot spot is located and being able to immediately assess the situation. Further, land management options can be considered and action planning started. For example, if a backburn is decided a best course of action, the steep slopes where the hot spots are located require a slightly different approach than the flat lands above. A GIS is designed for this type of fusion activity, providing a more complete sight picture to decision makers.

In Figure 28, 1 August is compared to 14 June. The change to the area through the fire season is apparent. Many south facing hot spots have grown some, and additional spots have emerged on other south and southwest facing slopes. While not illustrated, the areas were again checked for shade; there is no reason to think the hot spots are false positives. The north drainage, too, is still greener than everything else around it. In total, the area has a higher FSI (evidenced also by comparing the insets from Figure 27, above, and Figure 28, below). (A formal change detect algorithm is discussed in Chapter 5 as future work.)

To confirm the appearance that the FSI for the area around Mountain Home AFB, as a whole, had indeed risen and was not in error, several NFDRS inputs and outputs for the Mountain Home fire weather station were compared for the two dates. The station is located 2 mi east and 2 mi south from the southeast corner of the main base. A summary

Mountain Home Air Force Base Fire Susceptibility 14 June 2013 & 1 August 2013

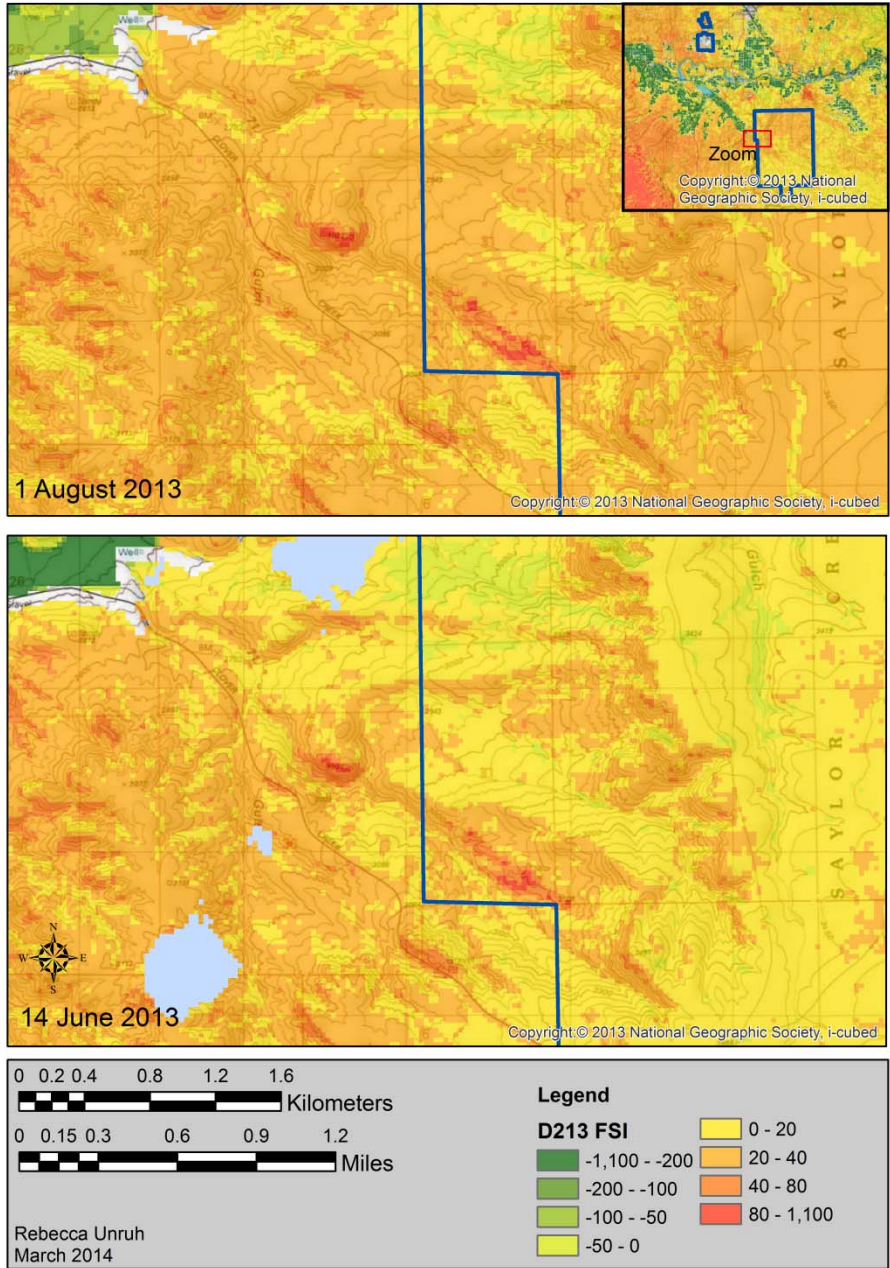


Figure 28: FSI Changes From 14 June to 1 August 2013

is below in Table 4. (For archive access, see Appendix B under USFS Wildland Fire Assessment System.) All signs point to the higher FSI in August to be correct. The dead FMC for 100- and 1,000-Hour fuels was lower in August. The Burning Index (BI) shows a fire in August would be equally as difficult to control, but the Ignition Component (IC) shows the probability of a firebrand starting a fire requiring suppression goes up from 35% in mid-June to 44% at the beginning of August. Recall, Dasgupta stated the FSI could be useful in estimating the probability of a firebrand starting a fire (5:144). As a result, it is expected that changes to the FSI would mirror changes to the IC. Even with raw Landsat data needing better calibration, the August FSI shows a trend of increasing one class, giving an increase of 1-39% of average fire susceptibility. As quantifying the relationship between FSI and IC is not an aim of this thesis, there was no further investigation. Finally, because the staffing index is the BI, the overall fire danger rating has remained the same: Moderate. The total correlation between NFDRS and the results of the method used here further supports the position that the FSI is performing well.

Table 4: NFDRS Observations for Mountain Home Fire Weather Station, #1 (32)

NFDRS Observations for Mountain Home Fire Weather Station						
Date	Temp (°F)	100-Hr FMC	1,000-Hr FMC	Burning Index (BI)	Ignition Component (IC)	Adjective Fire Danger Rating
14 June	66	6	8	39	35	Moderate
01 August	90	4	5	39	44	Moderate

Creating Masks: Removing Urban Development and Open Water

The result of removing urban land cover and open water is shown in the map below, Figure 29. The map shows the main base and airfield. Using land cover codes, urban development and open water have been removed (there are water retention ponds to the west of the flight line) (see Chapter 3 for discussion on creating the masks and extracting the FSI). Masking out this data removes distractions for the user. Both of these areas will appear as hot spots, even though, as discussed in Chapter 3, the calculated FSI is meaningless. Instead, the eye is drawn to investigating the open wildland, especially that surrounding development.

The USGS Topo beneath the FSI layer identifies structures and other base landmarks. Displaying these two layers together gives intuitive information that helps in the greater risk assessment and hazard risk management processes. As discussed in Chapter 2, a risk assessment considers both likelihood and consequences. The likelihood, the calculated FSI, has a spatial component. The consequences of a wildfire behind base housing is perhaps different from one on the west side of the airfield, and is further different from one on either range. While this methodology does not formally address the consequences, is it readily apparent how using a GIS as a decision support tool helps the user make those assessments in a way that plain numbers on a chart never can. Monitoring the state of the vegetation east of base housing or north of the hospital through the fire season is advisable. Using high resolution remote sensing data in a GIS instead of a land survey on foot fundamentally changes the way this is accomplished.

Mountain Home Air Force Base Fire Susceptibility 14 June 2013

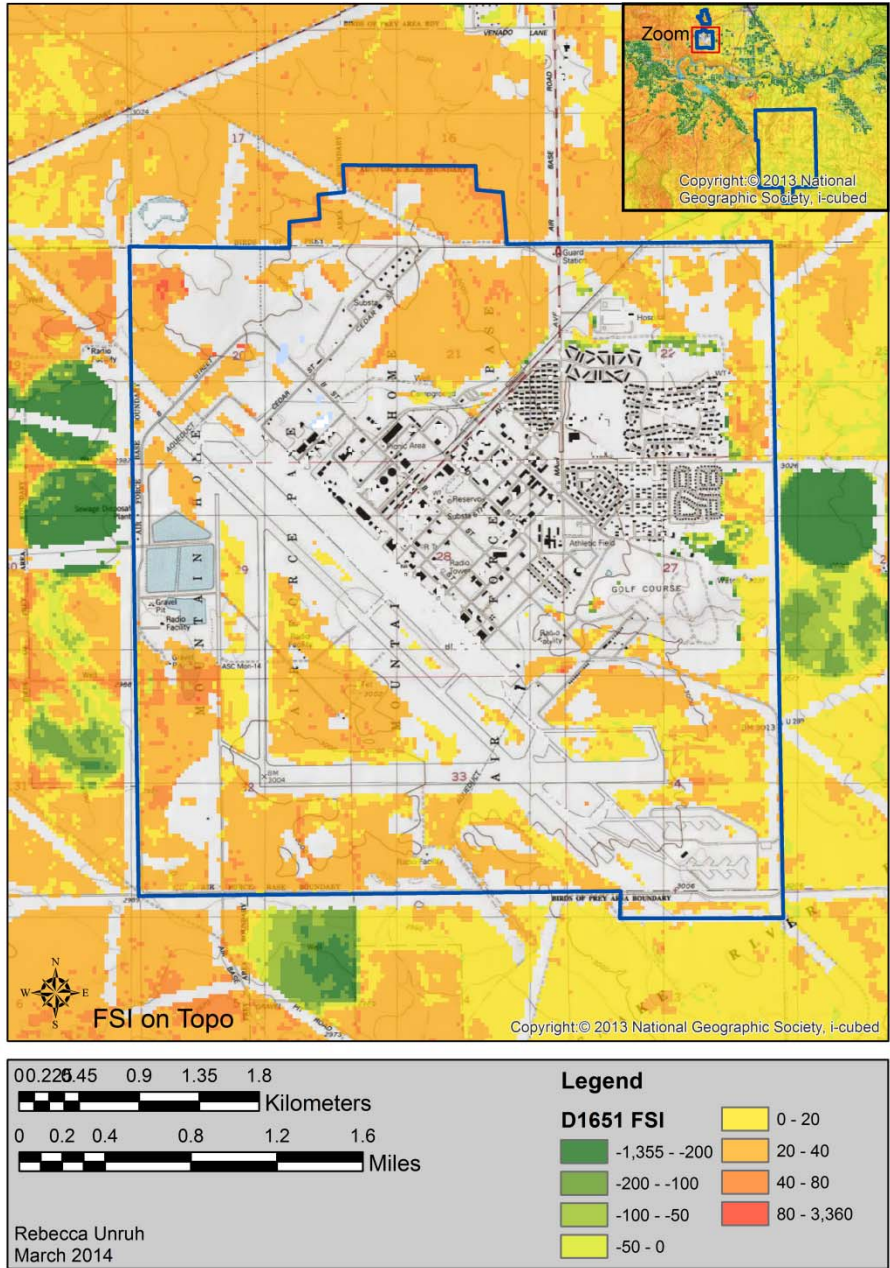


Figure 29: FSI with Urban Development and Open Water Removed

Adding Layers: Clouds, Snow, and Other Artifacts

The Landsat 8 Quality Assessment (QA) Band is arguably pixel by pixel metadata: Bands 1-11 underwent a fusion process by USGS to extract information on the content quality for each pixel. With all remote sensing data, tracking remaining artifacts and quality issues in an image is a fundamental necessity to prevent data assessment errors. The specific importance of identifying clouds, snow cover, and other artifacts while assessing an FSI calculation was discussed in Chapter 3. To illustrate this, Figure 30, a map from 18 September, is shown below.

Using the Landsat 8 Quality Assessment (QA) Band, clouds were placed back into the scene in a separate layer and symbolized in light colors. The shadows beneath them show up as false hot spots but noticeably follow the same outline as the white and grey clouds above. These areas can be ignored; assessing the fire susceptibility here is not possible.

What is noteworthy, however, is how much greener the remainder of the scene appears in comparison to 1 August in Figure 28 (see inset). Recall the large amount of rain that fell out west the first half of mid-September; the Mountain Home RAWS station saw ~0.5". The fuel has responded accordingly. Table 5, below, reviews the NFDRS observations for that day in comparison to 1 August. Temperatures were lower, and the dead FMC had increased. The BI, however, remains up at 31 (the winds were higher that day, and nearing the end of the season, the total dead fuel load is likely higher), and because the staffing index for the adjective rating at Mountain Home fire weather station is the BI, the fire danger rating remains at Moderate. The IC, most closely related to FSI, is down to 23%. It is not surprising then that a reduction in the FSI is seen.

Mountain Home AFB Fire Susceptibility 18 September 2013

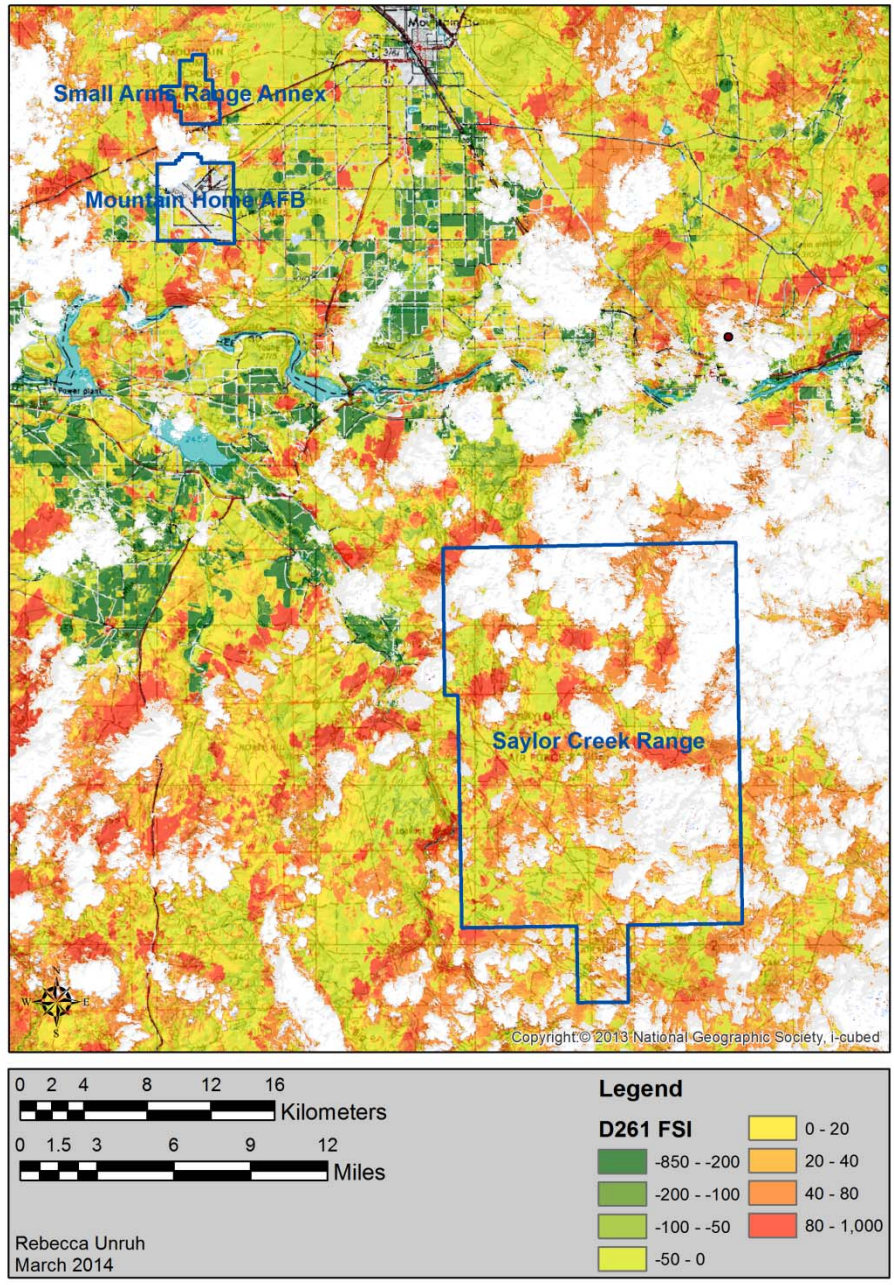


Figure 30: Effects of Cloud Cover

Table 5: NFDRS Observations for Mountain Home Fire Weather Station, #2 (32)

NFDRS Observations for Mountain Home Fire Weather Station						
Date	Temp (°F)	100-Hr FMC	1,000-Hr FMC	Burning Index (BI)	Ignition Component (IC)	Adjective Fire Danger Rating
01 August	90	4	5	39	44	Moderate
18 September	65	11	11	31	23	Moderate

From a decision support perspective, the fact that the FSI changed and the NFDRS adjective did not should not be dismissed. No two decision support tools approach a subject in the same way. NFDRS was designed to consider several aspects of wildfire behavior and assess fire danger ratings for large tracts of land. The tool developed for this thesis was designed to identify areas of concern within the WUI based on the heat energy of preignition. As stated in Chapter 2, there are other indices, as well as the NOAA fire weather forecast, available if applicable to particular decision. Considered together, the installation commander has an even more complete view of the current situation with respect to fire danger on and around base.

Source Data Resolution

The final observation that must be made is one of data resolution and scale. The decision to use Landsat 8 data for its 30 m ground spatial distance was discussed in Chapters 2 and 3. While exploring the results and rendering them alongside a scale in a map it is clear how much of a game-changer the higher resolution of Landsat is over the 1 km of other satellites. As shown in Figure 31; below; identifying, analyzing, and tracking the hotspots shown in the top frame is not possible with the larger, simulated 1 km pixels in the bottom frame (the raster was resampled at a larger grid size, averaging

the values of the smaller 30 m grid.). Combining the reflectances and emissivities over the square kilometer into one pixel resulted in an insignificant difference among neighboring cells. Furthermore, determining where in the terrain the hot spots were, and ruling out areas in shade would not have been possible. From Dasgupta, it was known working on a large cartographic scale was not possible with 1 km resolution. Seeing just how useless the low resolution data is when applied to the issue of land management in the WUI could not be grasped without first seeing the results of the high resolution data. No matter how powerful the GIS or novel the fusion method, without the right data, there is no meaningful information to support decisions, the work here demonstrates this.

Closing

Analyzing the results of the FSI calculations with Landsat 8 data in this chapter has found the method presented in Chapter 3 performed very well and is quite promising as a tool for assessing wildfire risk in the WUI, and not just on military installations. Even without the recalibrated Landsat data and allowing the top of atmosphere brightness temperature to stand in for surface temperatures, the initial validation with elevation data in considering the aspect of the landscape identifies the expected south and southwest hotspots and greener northern slopes. Total scene considerations, too, seem to mirror what is seen from the NFDRS IC for the area. Further validation is necessary, including ground survey throughout the next few fire seasons, as discussed in the final chapter. Calculating the FSI without the data fusion with other sources, as demonstrated here, drastically reduces its decision support utility. It was also demonstrated how

Mountain Home Air Force Base Fire Susceptibility 1 August 2013

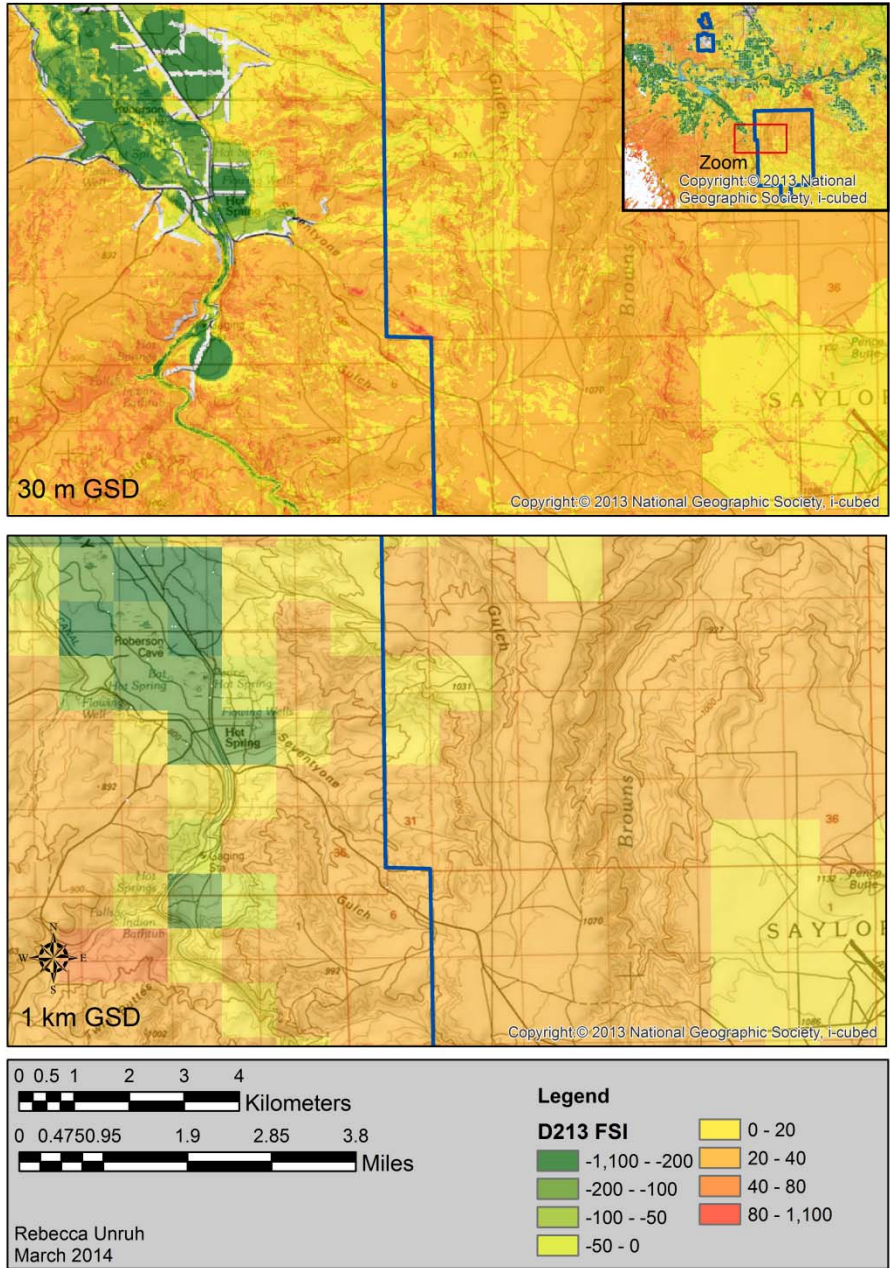


Figure 31: Comparing 30 m and 1 km Data

instrumental a GIS is in performing the analysis and sharing the results of spatial problems using spatial data.

V. Discussion

Conclusions

This thesis has demonstrated the utility of fusing data from multiple sources, including remote sensing data, in a Geographic Information System (GIS) for decision support. Using information from remote sensing systems for decision support is not new and neither is data fusion. The opportunities for fusion have grown, however, as computing power and networks have grown. The GIS has emerged as an ideal fusion platform and decision support tool by relating data based on spatial attributes. Since most remote sensing data is time and location tagged, it is possible to correlate, fuse, and co-render disparate data sources in a GIS, from which data can be stored, analyzed, and the resulting information shared.

To demonstrate the utility of this type of data fusion, decades of work in fire science and emergency management were examined and enlisted to provide an entirely new view of wildfire risk in the wilderness urban interface (WUI), where so many military installations are found. Applying the Fire Susceptibility Index (FSI) to Landsat 8 data provides insight at a 30 m scale unprecedented in the state of the practice in wildland management. Incorporating periphery assessment and orientation data and features into the decision making tool catalyzed the transition from quantitative data to usable information. An installation commander can look at the FSI output laid over elevation and orientation information and say, "There is a hot spot; it is on a steep southwest facing slope with base housing on the other side of the rise." Now they have both knowledge of

the potential hotspot and contextual information to help make a better decision.

Understanding fire behavior, they know it will continue to take the brunt of the sun's rays because of its aspect. They know that if a fire starts it will spread uphill quickly, and that with the proximity to base housing, response time is limited, and potential mission impact is high. The spectrum of quantitative and qualitative analysis becomes available in one decision support tool. The same tool can also communicate risk in a meaningful way with information that is easy to both share and understand. The base fire chief can then develop and execute mitigation efforts, using additional existing decision support tools. All of this a result of data fusion, made possible by powerful GIS and no fewer than eight data sources that were properly georeferenced, documented, and made freely available to an unplanned user for an unplanned purpose.

With advances in remote sensing, geotagging data, data fusion efforts, computing power, networking, and GIS in the past few years, the possibilities for finding information in data has grown exponentially. It is important that programs are technically prepared to share data, both existing programs and new acquisitions. Technical preparation requires getting data into standard formats so it can be brought together in a GIS and requires publishing the metadata necessary for a user to determine its suitability and employ it successfully in whatever project they are undertaking. Even if data is never shared externally to the organization, freely sharing data internally has the ability to increase knowledge and productivity without the costs and infrastructure overhead associated with supporting a new program with its own dedicated data stream. The same benefits are found multiplied when data sources can be shared wider afield.

Future Work

There are several projects that build on from work here that would be worthwhile to pursue. The first five below are quite specific and deal with further work with the FSI and wildfire in the WUI. The last is a general area of further work to revamp existing stovepiped remote sensing programs within the military.

As discussed in Chapters 1 and 3, this tool should be updated with the recalibrated Landsat 8 data and its split-window algorithm for surface temperature, when published. In particular, the regression equation should be rebuilt, and the split-window algorithm built onto the back of the top of atmosphere brightness temperature tools (although not used for the FSI calculation, the Band 11 tool was built and tested). After updates, the results should be validated with field observations. Like many of its predecessors, it may take several years before the calculated results are fully understood; and a certain amount of local knowledge must accompany the tool's use.

Regression equations should be built for other fuels and tuned to disparate areas across the country where military bases exist in a WUI. To expedite this, collection of field FMC data should be coordinated with planned Landsat 8 flyovers, especially in areas where the National Fuel Moisture Database currently lacks sufficient observations for an area. The survey of the 2012 and 2013 fire seasons in Chapter 2 shows no part of the country is immune to this problem. Overseas and deployed locations should be considered as well, although a database of fuel moistures will have to be built from new field data or otherwise obtained.

This toolset could benefit from a change detect algorithm. While a visual assessment did work because of the way the FSI was symbolized and the USGS Topo

helped orient the user in the data, a change detect algorithm would remove error in user perception and formally quantify the changes. Two of the more difficult areas will be: 1, dealing with cloud and snow cover, shadows, and other obstructions, and 2, identifying and working with flooded areas in the corners of the irrigated farm fields and other land periodically covered with water. This change detect algorithm can be built and executed in the GIS.

Dasgupta had outlined a method for incorporating the dead fuels in the FSI, but it was never pursued because of the difficulty of accessing the ground beneath the canopy with remote sensing. Incorporating the dead fuel in the FSI should be revisited in search of a novel solution. Fusing multiple sensor sources, including lidar, may provide the answer.

In an effort to bound the scope of this work, the focus was on using remote sensing data in a GIS for decision support. In truth, the use of this data continues into the larger realm of operations support. The same fusion inputs and outputs can feed further fusion activities as needed. For example, the FSI information can be used to fight a wildfire if one starts with Rothermel's models, plan and execute back burns, or simply limit activities on the range. One or more of these areas could be further investigated.

Digressing from the wildfire problem, existing efforts working with remote sensing data within a stovepipe processing chain across the community should be reviewed with an eye toward fusion. There are really two efforts here. First, identifying and proposing solutions to shortcomings in how the data, both raw and post-processed data and features, is being handled, processed, documented, and stored that prevent it from being used in further fusion efforts. This thesis used a plethora of data sources

openly available from across multiple government agencies, only possible because it was purposefully designed for sharing. Second, the process should be examined for where the output product could benefit from further fusion. Many programs today do some sort of fusion, especially data in-data out fusion close to the raw data from multiple sensors in a single system. Still, these processes are stovepiped and may benefit from cross-program fusion. Spatial problems, especially, would benefit from utilizing a GIS to identify new relationships among data sets. Until data is in a format capable of multiple-source fusion, the opportunity lost is not necessarily readily identifiable. The possibilities provided by today's operating environment, however, are encouraging.

Appendix A: Wildfire Basics

The Wildfire Behavior Triangle

Understanding wildfire terminology and concepts is necessary to identify and have a conversation about how remote sensing can play a part in assessing wildfire risk. One way to understand wildfires is looking at the wildfire behavior triangle, depicted below in Figure A1. The three sides, fuel, topography, and weather, are the three factors at play in determining wildfire behavior. The assessment of fire danger, previously introduced and a focus for this thesis, is not the same as fire behavior modeling. However, fire behavior is considered to various degrees when assessing fire danger. Fire behavior modeling is often used in fighting wildfires and setting up prescribed burns, among other things. Here fire behavior is explored because it illustrates the physics behind wildfire. We will explore some basic wildfire terminology, the classification of fuels, and the influence of topography and weather.

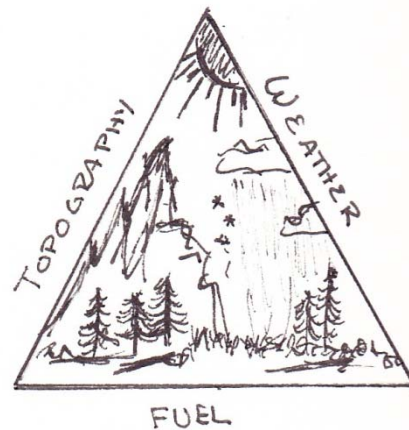


Figure A1: Wildfire Behavior Triangle

Fuels

The base of the wildfire triangle (Figure A1), understanding fuels, their physical and chemical properties, is fundamental for both modeling wildfire behavior and assessing a wildfire danger rating. Without fuel, there is no fire. While the underlying physics of burning fuels does not change, modeling fuels for fire behavior and fire danger rating is approached slightly differently. Fire behavior looks at fuel type, loading (tons per acre), availability (related to surface area to volume ratio), and arrangement (considering horizontal continuity and vertical arrangement) (30:2B.3-2B.10). Based on this fire behavior, NFDRS identifies six basic fuel models (lichens and mosses; marsh grasses and reeds; grasses and forbs; brush, shrubs, and tree reproduction; trees; and slash). Most are further subdivided, creating a total of twenty fuel models. Detailed descriptions can be found in both the NFDRS and NWCG documentation. Dry fuel burns much easier than wet fuel. Fire danger rating focuses on monitoring fuel moisture content (FMC), “the quantity of moisture in fuel expressed as a percentage of the weight when thoroughly dried at 212 degrees F” (26:88). At some point, the fuel contains enough moisture fire can no longer spread; this is known as the moisture of extinction (26:123). This fuel moisture changes rapidly in some fuels and quite slowly in others. It is affected by weather and topography, the other two sides of the wildfire behavior triangle, as we will see in the next two subsections. NFDRS danger ratings model fuel moisture content based on the mechanisms that control moisture content. There are two classifications: dead and live.

“Dead fuels are fuels in which the moisture content is exclusively controlled by environmental conditions [weather]—temperature, radiation, relative humidity, and

precipitation” (55:5). Dead fuel models are based on a timelag, the amount of “time necessary for a fuel particle to lose approximately 63% of the difference between its initial moisture content and its equilibrium moisture content” (26:172). Naturally, the timelags follow exponential decay curves (for details, consult the work of Byram and Fosberg in the NFDRS documentation). The equilibrium moisture content, the “moisture content that a fuel particle will attain if exposed for an infinite period in an environment”, changes with temperature and humidity (26:67). The dead fuels are further divided into four classes by their timelag: 1-, 10-, 100-, and 1,000-hour timelag fuels. These divisions are based on the changes in moisture content from “weather cycles of 1-day (diurnal), 4-day (synoptic), 30-day (planetary), and 1- year (annual)” (55:6). Figure A2 summarizes the roundwood size and location within the duff of dead fuels, described below; the definitions are found in the NWCG Glossary (26). The models relating the timelag and fuel moisture content were developed by Byram and Fosberg from the 1950s through the 1970s are based on both field observations and laboratory work and are modeled in NFDRS.

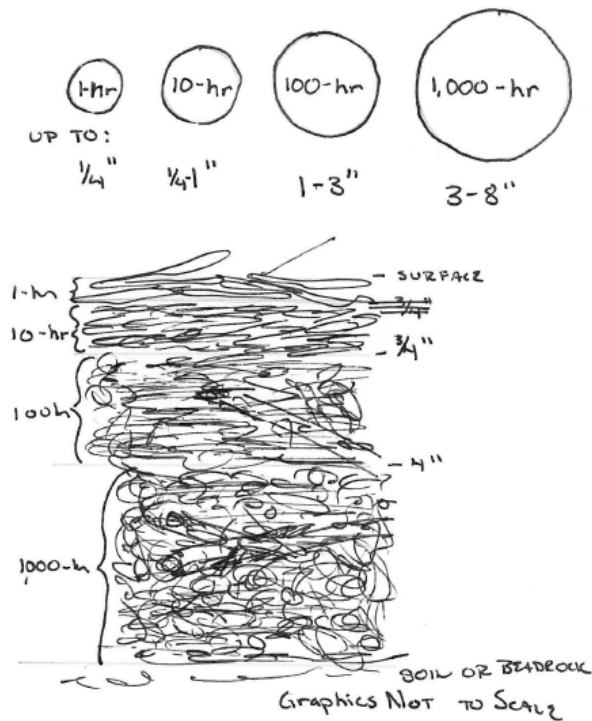


Figure A2: Dead Fuels

Live fuels are “living plants, such as trees, grasses, and shrubs, in which the seasonal moisture content cycle is controlled largely by internal physiological mechanisms, rather than by external weather influences” (26:114) For modeling purposes, they are further divided into two classes: herbaceous plants (both annual and perennial grasses, forbs, and ferns) and woody shrubs (all perennial). As the growing season progresses through greening and curing, woody shrubs go dormant, and herbaceous plants are added to the 1-hour timelag fuels. The changes in live plants as they progress through the growing season and are subject to environmental stress is detectable with remote sensing. The annual changes and responses to environmental stressors vary greatly from one species to another and arguably even from one population to another. The sure way to acquire current live fuel moisture is to collect field samples

and calculate the difference in weight before and after oven drying; this is a labor intensive method. Work to understand remote sensing data and accurately model live fuel moisture content continues.

Topography

Topography describes the relief of a surface. Topography affects both fire danger and fire behavior by influencing fuel moisture content and weather. According to the NWCG, of the three factors of wildfire behavior, topography has the most predictable effect (30:2A.3). There are four elements of topography to explore: elevation, slope, aspect, and terrain. Given the first element, elevation, we can derive and analyze the other three elements. This is easily done with a good data set in a GIS system.

Elevation is the distance or height of any point above another, usually mean sea level (30:2A.6). It affects fire danger and behavior by effecting weather and available fuels. Elevation can influence the temperature, amount of precipitation, and wind exposure (30:2A.6). It also dictates the type and size of plants that can grow; this changes the type of fuel modeled in determining a fire danger rating or predicting fire behavior (30:2A.6).

Given a pair of elevations at two known locations, a slope can be determined. Slope describes the steepness of a surface in degrees or percent of slope. Slope effects how fires burn and how firefighting personnel fight them. A fire will spread uphill faster than it will downhill because of the heat transfer; the steeper the slope, the greater the effect. Also, a sufficiently steep slope, depending on groundcover, may not be safely

accessible to emergency personnel. The presence of a slope, in turn, gives a surface aspect and terrain (30:2A.4).

Aspect measures the direction of slope. It is usually expressed in degrees or a direction on a compass. Aspect is important in considering fire danger because it influences the amount of sun, wind, and precipitation a surface, and in turn the fuel, is exposed to. Generally, south and southwest slope receive more sunlight resulting in higher temperatures, lower humidity, and lower fuel moisture (30:2A.3). Historical evidence shows these slopes “are the most critical in terms of [the] start and spread of wildland fires” (30:2A.3). Conversely, north facing slopes see less fire activity with lower temperatures, higher humidity, and higher fuel moistures (30:2A.4). Similarly, prevailing winds can regularly expose one aspect to different conditions (perhaps more hot dry air or more precipitation) than another. This is even more pronounced when we consider certain topographic features.

Slope and its aspect give a surface terrain or topographic features. Some common topographic features include: ridges, hilltops, spurs, saddles, draws, valleys, canyons, cliffs, and depressions. When predicting fire behavior or fire danger, we find certain features have the ability to create their own regular weather patterns. Canyons of various forms create their own regular wind patterns (30:2A.5). The updrafts created by box canyons, for example, result in extreme fire behavior, making them dangerous to emergency personnel. Features also influence the mechanics of the hydrologic cycle in an area. For instance, as water moves downhill to collect in draws and valleys, live fuels there may have access to more water.

Topography is easily modeled and analyzed in a GIS. Aerial, and more often space based, remote sensing systems (usually lidar or radar) are used to acquire elevation information. Once the elevations are properly formatted and geo-tagged, they are ready for use in a GIS. From there, slope and aspect can be derived, terrain features determined, and the data can be used to assist with further analysis. The USGS NED has the most comprehensive collection of elevation data for the United States.

Weather

Weather is the third and most temporal side of the wildfire behavior triangle. Weather is constantly monitored by fire crews and emergency responders while fighting a wildfire or conducting a prescribed burn. Lightning from a storm can ignite a wildland fire, hot dry winds can help a fire spread rapidly, and a long overdue rain shower can extinguish one. While the weather itself is highly temporal, its effects are cumulative. As such, they are extremely important in models for creating a fire danger rating. Here is an overview of the five basic concerns in fire weather: air temperature and relative humidity, precipitation, atmospheric stability, and wind. Lastly, we will briefly look at fire weather how the National Weather Service (NWS) is involved.

Air temperature and relative humidity change with respect to time, location, and elevation. “Relative humidity is the amount of moisture in the air divided by the amount the air could hold when saturated at that same air temperature; usually expressed in percent” (30:2C.5). This moisture “is the primary weather element [affecting] fuel moisture content and the resulting flammability of wildland fuels. As alluded to in the discussion on timelag, this relative humidity affects the amount of moisture fuels can

absorb or release” (30:2C.5) .Relative humidity does not stand alone, however; it is inversely related to the current air temperature. Increasing air temperature decreases relative humidity and vice versa. As sunlight heats the atmosphere and the Earth’s surface, fuels are heated, dried, and brought closer to preignition and ignition (30:2C.5). The temperatures or energy levels required to bring fuel to preignition are well understood physical properties modeled in fire danger indices and fire behavior algorithms.

The second consideration for fire weather is precipitation. Precipitation effects fuel moisture content with its total amount and, more effectually, with its duration (30:2C.8). Different fuels absorb the moisture at different rates. Topography changes how the water moves through the environment. The longer the exposure to moisture, the greater the amount fuels absorb and the farther they get from their ignition point.

Atmospheric stability has the greatest effect on wildfire behavior. “Atmospheric stability is the degree to which vertical motion in the atmosphere is enhanced or suppressed; ...a stable atmosphere...resists upward motion” (30:2C.9). This vertical motion is of particular concern for wildland fire since wildland fires increase in intensity and temperature with increasingly unstable air as it supplies the fire with increased oxygen for combustion. Inversions, where temperature increases with altitude, are also considered here because as they set and later lift, the new air mass can enflame or suppress wildland fire according to its temperature and relative humidity. While it may not create an immediate effect on fire danger, the effects on wildfire behavior have atmospheric stability under close watch of firefighters and emergency personnel in the field.

Wind, “the horizontal movement of air relative to the surface of the earth, ...is the most critical weather element affecting wildland fire behavior, the most difficult to predict, and the most variable in both time and location” (30:2C.15). As discussed in the previous section, topography, along with bodies of water, can influence the wind patterns at a site; as topography variation increases, so does the creation of local wind patterns (30:2.C.16). Wind, fire or not, increases the drying of fuels. For this reason, it is considered both in modeling fire danger and fire behavior. Once a wildland fire has started, wind is of particular concern as it supplies the fire with oxygen, determines the direction the fire spreads, causes spotting by spreading firebrands, and reduces the resistance time of fuels to ignition (30:2C.15).

“Weather conditions which influence fire ignition, behavior, and suppression” is known as fire weather (26:79). Fire weather “periods are characterized by...strong and shifting wind, very low relative humidity, high temperature, [an] unstable atmosphere, and dry lightning” (30:2C.22). An area’s seasonal weather patterns often create one or more fire seasons where the likelihood of these conditions is increased. The fire season is, indirectly, considered when determining fire danger ratings. The National Weather Service (NWS) has a fire weather program that tracks and forecasts fire weather (see Appendix BB under NOAA – National Weather Service Fire Weather). Among many other things, the NWS produces Fire Weather Forecasts (FWF), issues Fire Weather Watches and Red Flag Warnings, and publishes a National Situation Report.

Fire Weather information is a key piece of decision support with respect to wildfires as it greatly affects both wildfire behavior and fire danger rating. The second

and third order effects of weather on fuels manifest themselves in remote sensing data. Historic weather information can validate trends seen in FMC calculations from that data.

NFDRS Inputs and Outputs

The USFS technical documentation containing the many algorithms, lookup tables, and fuel models behind this is extensive, lengthy, and split into 3 documents. The basic equations alone populate their own 16 page document. For this reason, they are not shared. Here is a short introduction of the NFDRS inputs and outputs; further detail and source documents are available from the USFS and NWCG.

Using WIMS, NFDRS takes a series of inputs, fuses the data, and calculates a series of outputs daily. The graphic below, Figure A3 is from the NWCG and tracks the NFDRS inputs, intermediate calculated values, and output data.

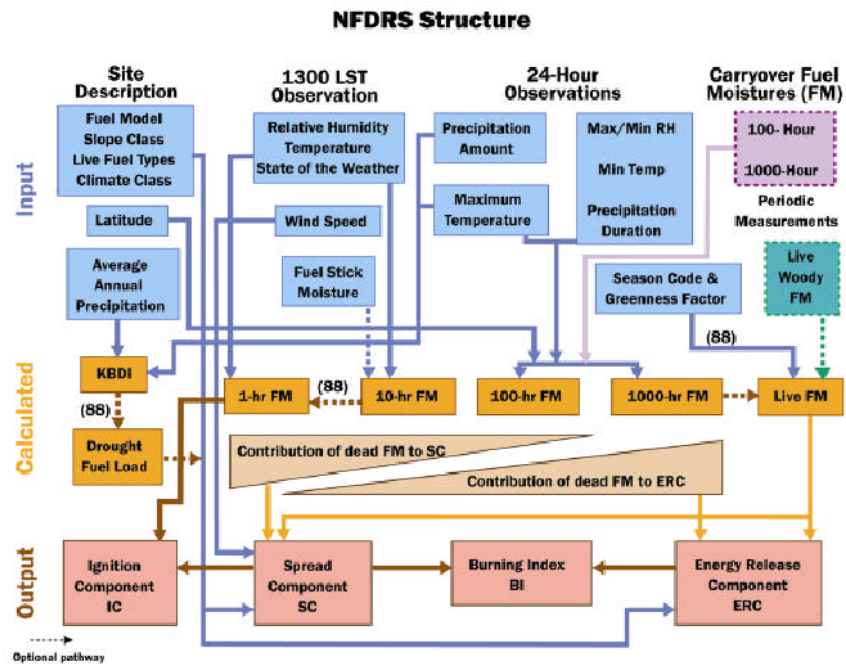


Figure A3: NFDRS Structure (27:38)

NFDRS Inputs

Describing the system inputs, the NWCG breaks NFDRS structure into three parts: the scientific basis, the user controlled site descriptors, and the data. The first two parts are easily described. The scientific basis consists of the series of mathematical models used in the calculations. These models are based on the underlying physics of wildfire behavior surveyed in the previous subsections. The user controlled site descriptors are used to describe the fire danger rating area. The fire danger rating area is defined as “a geographical area of generally homogenous fuels, weather, and topographic features, tens of thousands of acres in size” (27:12). Accurate site descriptors are necessary for the mathematical models to produce meaningful outputs. The site descriptors include fuel models, slope class, grass type, climate class, and annual precipitation. These site descriptors are usually static but can be adjusted to improve system output.

The data refers to NFDRS inputs that change at and are reported in WIMS at regular various intervals at fire weather stations by local users. The fire weather stations are operated by the local land or fire management agency: USFS, BLM, NPS, etc. Data includes weather observations and predictions; vegetation information; climate and season information; and agency decision making parameters.

Weather observations are either collected manually or from a Remote Automated Weather Station (RAWS) operated at the fire weather station. The RAWS network contains nearly 2,200 stations (56). The data is forwarded via GOES to the National Interagency Fire Center (NIFC) in Boise, Idaho, and onto WIMS (56). Weather predictions come from the NWS. NFDRS is sensitive to the quality and regularity of

weather data; a missed day of input results in no fire danger prediction for the following day (we will see evidence of this in the next section).

A series of other parameters must also be periodically recorded and input to WIMS: state of herbaceous vegetation (growing, curing, or dormant), shrub type (deciduous or evergreen), measured woody fuel moisture (monthly physical field measurements of live woody fuel moisture), season codes and greenness factors (used in the 1988 models and requiring field observation), the season initiation for the Keetch-Byram Drought Index (KDBI) (used in the 1978 models), as well as, a staffing index selection with display class breakpoints (translates calculated NFDRS outputs into expected firefighting workload and the adjective fire danger rating). Much of this data is collected from field observations by trained and seasoned personnel.

NFDRS Outputs

NFDRS outputs can be broken into “intermediate calculations that serve as the ‘building blocks’ for the next day’s calculations and the indices and components that actually measure the fire danger” (27:21). Intermediate calculations are the fuel moistures (described earlier): herbaceous live fuel moisture, woody live fuel moisture, and the four classes of dead fuel moisture. These calculations require daily weather inputs. They are also checked and calibrated not less than monthly by collecting and measuring field specimens. NFDRS calculations output five indices and components as well as an adjective fire danger rating. Let’s take a look at each of these.

The first output is the Spread Component (SC). The SC “is a rating of the forward rate of spread of a headfire...expressed in feet-per-minute” (27:24). The SC is a theoretical value that often varies day to day and has no upper limit (27:24).

The second output is the Ignition Component (IC). The IC “is a rating of the probability [(values of 0 to 100)] that a firebrand will cause a fire requiring suppression action” (27:23). In other words, it is a probability that a fire will ignite and spread. As such, SC values are used in its calculation (27:23).

The third output is the Energy Release Component (ERC). The ERC “is a number related to the available energy (BTU) per unit area (square foot) within the flaming front at the head of the fire,” or “‘heat release’ per unit area” (27:24). This value reflects not just fuel moisture, but also drought and the buildup of fuel in the rating area (27:24). The ERC is more stable than the SC and IC, and it has no upper limit (27:24).

The fourth output in the Burning Index (BI). The BI is “an estimate of the potential difficulty of fire containment” (6:40). It has an open ended scale and “is derived from a combination of [SC] and [ERC]” (27:24). The higher the value, the more difficult a fire will be to control.

The fifth output is the KDBI. The KDBI “is an estimate of the amount of precipitation (in 100ths of inches) needed to bring the [top eight inches of] soil back to saturation” (27:27). KDBI is “used to measure the effects of seasonal drought on fire potential” (27:27). Increased KDBI corresponds with increased vegetative stress, drying of duff, and the transfer of live fuels to the dead fuel load” (27:27).

Finally, NFDRS is used to determine an adjective fire danger rating: Low, Moderate, High, Very High, and Extreme. The adjective fire danger rating is based on the fire

weather station’s “first priority fuel model”, the IC, and the station’s staffing index (the index used, usually ERC or BI, to set staff levels) (27:29-31). The fire adjective ratings and descriptions are summarized below in Table A1.

Table A1: NFDRS Adjective Fire Danger Ratings (27:30)

Adjective	Description
Low	“Fuels do not ignite readily from small firebrands although a more intense heat source, such as lightning, may start fires in duff or punky wood. Fires in open cured grasslands may burn freely a few hours after rain, but woods fires spread slowly by creeping or smoldering, and burn in irregular fingers. There is little danger of spotting.”
Moderate	“Fires can start from most accidental causes, but with the exception of lightning fires in some areas, the number of starts is generally low. Fires in open cured grasslands will burn briskly and spread rapidly on windy days. Timber fires spread slowly to moderately fast. The average fire is of moderate intensity, although heavy concentrations of fuel, especially draped fuel, may burn hot. Short-distance spotting may occur, but is not persistent. Fires are not likely to become serious and control is relatively easy.”
High	“All fine dead fuels ignite readily and fires start easily from most causes. Unattended brush and campfires are likely to escape. Fires spread rapidly and short-distance spotting is common. High-intensity burning may develop on slopes or in concentrations of fine fuels. Fires may become serious and their control difficult unless they are attacked successfully while small.”
Very High	“Fires start easily from all causes and, immediately after ignition, spread rapidly and increase quickly in intensity. Spot fires are a constant danger. Fires burning in light fuels may quickly develop high intensity characteristics such as long-distance spotting and fire whirlwinds when they burn into heavier fuels.”
Extreme	“Fires start quickly, spread furiously, and burn intensely. All fires are potentially serious. Development into high intensity burning will usually be faster and occur from smaller fires than in the very high fire danger class. Direct attack is rarely possible and may be dangerous except immediately after ignition. Fires that develop headway in heavy slash or in conifer stands may be unmanageable while the extreme burning condition lasts. Under these conditions the only effective and safe control action is on the flanks until the weather changes or the fuel supply lessens.”

Appendix B: Web Resources

7-Zip – <http://www.7-zip.org/>

7-Zip is open source software that packs and unpacks high-compression files, the Landsat 8 imagery for this thesis.

Inciweb – <http://inciweb.nwcg.gov/>

Inciweb is a portal to current and past wildfire incidents including: updates on conditions, press releases, photographs, and maps.

Missoula Fire Sciences Laboratory - www.firemodels.org & www.firelab.org

The Missoula Fire Sciences Laboratory has a portal to many fire behavior and fire danger models and associated data at firemodels.org. They have a second portal, firelab.org, that contains models and data related to fire physics, including combustion, fuels, and smoke.

National Fire and Aviation Management Web Applications (FAMWEB) –

<https://fam.nwcg.gov/fam-web/>

This site is maintained by NFIC. Much data is collected and accessed here including: WIMS, FIRESTAT (Fire Statistics), Situation Reports, the Annual Wildfire Summary Report (AWSR), and the USFS Aviation Management Information System (AMIS), among other things. A log-in is required for much of the content.

National Fire Information Council (NFIC) – www.nfic.org

Collects and disseminates fire-related (not just wildfire) emergency response information.

National Fuel Moisture Database (NFMD) – www.wfas.net/index.php/national-fuel-moisture-database-moisture-drought-103

national- fuel- moisture-database-moisture-drought-103

Collection of field measured fuel moistures, organized by location, plant or dead fuel class, and date.

NOAA National Climatic Data Center – www.ncdc.noaa.gov

NOAA has a wide variety of data available through their National Climatic Data Center. The data comes from many platforms including: weather stations, weather balloons, radar, and satellites, among others. They also have archives of modeled weather patterns and severe storms. All of the data is complete with associated metadata.

NOAA – National Weather Service Fire Weather – www.srh.noaa.gov/ridge2/fire
National Weather Service (NWS) has a fire weather program that tracks and forecasts fire weather. There are also links in here to ROMAN and RAWs for historic fire data.

United States Drought Monitor - www.cpc.ncep.noaa.gov/products/Drought
National Weather Service Climate Prediction Center does much work monitoring drought conditions. These drought conditions lead to increased fire activity, and understanding that link is important to understanding fire danger and behavior. The portal for the US Drought Monitor is accessible from the NOAA website. Here, many data products and years of archival data is available. Much of the data is also in a GIS friendly format. Some of the data and indices feed into the information seen on WFAS.

US EPA: Western Ecology Division– www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm
This link provides access to the Level III and Level IV GIS data for the Continental United States, including: the shapefiles, a symbology file, metadata, and instructions for applying the symbology to the ecoregions. PDF maps are also available from here, as well as links to other ecoregion information and data. Full descriptions of the Level III ecoregions are available in a word document. The level IV descriptions can be found in the .pdf posters by state or from the Encyclopedia of Earth website in an article coauthored by James M. Omernik, who developed the ecoregion framework (<http://www.eoearth.org/view/article/152243>).

US National Vegetation Classification – www.usnvc.org
Access the information on the USNVC System, its supporting documentation, and classification descriptions.

USGS Bulk Download Application – <http://earthexplorer.usgs.gov/bulk/>
This free software enables large downloads from USGS sites. It automatically manages your processed data orders and facilitates the download. A user name and password is required to access this product. It is the same user name and password used to download from Earth Explorer and GLOVIS.

USGS Earth Explorer – <http://earthexplorer.usgs.gov/>
Access and download Landsat 8 data from here. An account with user name and password is required for download. The same account works on GLOVIS. Because the data sizes are large (each set is roughly 1 GB, compressed), using bulk download was preferred. This requires downloading and installing the Bulk Download Application and a program for unpacking the high-compression .tar.gz files; I used the open source software 7-Zip without issue.

USGS Earth Resources Observation and Science (EROS) Center –

<http://eros.usgs.gov/find-data>

Access all sorts of USGS data from here.

USGS Fire Danger Viewer – <http://glovis.usgs.gov/>

Access and download current NDVI and FPI data from here. Archive data is here as well, but only in an image.

USGS Global Visualization Viewer – <http://glovis.usgs.gov/>

Access and download Landsat 8 data from here. An account with user name and password is required for download. The same account works for Earth Explorer. Because the data sizes are large (each set is roughly 1 GB, compressed), using bulk download was preferred. This requires downloading and installing the Bulk Download Application and a program for unpacking the high-compression .tar.gz files; I used the open source software 7-Zip without issue.

USGS National Gap Analysis Program – <http://gapanalysis.usgs.gov/>

This site provides information on the Gap Analysis Program (GAP). The GAP data and metadata is available for online viewing (with the viewer) and download.

USGS - Landsat Missions – <http://landsat.usgs.gov/>

Everything needed to access and begin work with Landsat imagery is accessible from this portal. The satellite band designations (http://landsat.usgs.gov/band_designations_landsat_satellites.php) are here, along with other technical documentation (http://landsat.usgs.gov/tools_project_documents.php). Instructions, including equations, for working with the Landsat 8 data products is here (http://landsat.usgs.gov/Landsat8_Using_Product.php), along with details on the Quality Assessment Band and how to decode it (<https://landsat.usgs.gov/L8QualityAssessmentBand.php>). An explanation of the World Reference System (WRS) is here. Shapefiles of WRS-1 and WRS-2 are also available for download (https://landsat.usgs.gov/worldwide_reference_system_WRS.php).

USGS - The National Map – <http://nationalmap.gov/>

The USGS has access here, through the viewer (<http://viewer.nationalmap.gov/viewer/>) to topo maps, used in this thesis, as well as dozens of other data sources. Some data can be downloaded, others can be displayed in Esri and Google maps with an internet connection.

USFS Wildland Fire Assessment System – www.wfas.net

Access and download current NDVI and FPI data from here. Access to NFDRS archive products, available by date; NFDRS daily station observations in text file. (<http://www.wfas.net/index.php/search-archive-mainmenu-92>) Archive access and download the NFDRS Fuel Model Map and documentation information here (<http://www.wfas.net/index.php/nfdrs-fuel-model-static-maps-44>).

Weather Information Management System – <https://fam.nwcg.gov/fam-web>

WIMS is accessed through FAMWEB (Fire and Aviation Management Web Applications), a website managed by the NWCG. A user account is needed to access WIMS. Here, fire weather station managers enter and edit daily observations and access the forecasted fire danger rating as well as the output components and indices for their area. For those without accounts, some of the information is retrievable through the WFAS and the NWS.

Western Regional Climate Center – <http://www.wrcc.dri.edu/>

Run by the Desert Research Institute (DRI), access and climate data from here, including RAWS for the entire nation.

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Vita

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Her first assignment was at the Space and Missiles Systems Center at Los Angeles AFB as a Project Officer working on 3rd Generation Infrared Satellite Systems. In July 2009 she was assigned to the Basic Research Division at the National Reconnaissance Office in Chantilly, Virginia, as a Program Manager. In January 2011, she moved over to the Missions Operations Directorate as the Executive Officer. In August 2012, she entered the Graduate School of Engineering and Management, Air Force Institute of Technology and upon graduation will be assigned to the Air Force Research Laboratories at Kirtland AFB in Albuquerque, New Mexico.

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14. ABSTRACT This thesis demonstrates the utility of fusing data from multiple sources, including remote sensing data, in a Geographic Information System (GIS) for decision support by designing a new method of assessing wildfire risk in the wilderness urban interface (WUI) to facilitate better informed land management decisions and reduce mission impacts of wildfires on the military. Information from remote sensing systems has been used for decades to support decisions. Today, data are time and location tagged, making it possible to correlate and fuse disparate sources in a GIS, from which data can be stored, analyzed, and the resulting information shared. The GIS, relating data based on spatial attributes, has become an ideal fusion platform and decision support tool. In demonstration, decades of work in fire science were put to work, applying the Fire Susceptibility Index (FSI) on a new, 30 m scale with Landsat 8 data. Eight data sources were fused in a GIS to identify high-risk patches of wildland by calculating the FSI and preparing it for meaningful analysis and sharing. The initial results, qualitatively validated with wildfire behavior basics, appear promising, providing a view of fire danger in the landscape not seen in the current state of practice.					
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