University of Nevada, Reno

# NDVI-derived Green-up Date for the National Fire Danger Rating System

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environmental and Natural Resource Sciences

Paul M. Schlobohm

Dr. Paul Tueller/Academic Advisor
Dr. Timothy Brown/Thesis Advisor

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## Abstract

A new method has been developed to objectively determine green-up dates for the National Fire Danger Rating System (NFDRS). This method has applications for the current point-data NFDRS and for possible future calculations of fire danger at higher spatial resolutions.

The objectives of this thesis are to propose two features of a live fuel moisture model for NFDRS in the 21$^{st}$ century. The first feature is a method to determine in “real time” the green-up date at 1-km spatial and 1-week temporal resolutions using Normalized Difference Vegetation Index (NDVI) from NOAA Advanced Very High Resolution Radar (AVHRR). The second feature is a process to determine historical green-up dates for historical analysis purposes.

The proposed method is the integration of area under a smoothed curve of NDVI from the curve minimum until the climatological green-up threshold is achieved. Application was made to historical data as if the method was being used operationally, that is, without knowledge of NDVI values outside each set of analyzed values.

Pixels were classified by the magnitude of their climatological NDVI signature. Three 3x3 pixel study areas were chosen to represent relatively flat (Nevada), moderate (Florida), and steep (California) NDVI signals. The proposed method was applied to 1-week maximum composite NDVI observations (1989-2002) from the three locations. Median green-up dates were late May-to-early June, late-mid April, and late September-to-early November, and variation around the median was 2-3 weeks, 2-5 weeks, and 3 weeks for the California, Nevada, and Florida sites, respectively.

**Acknowledgements**

This project is the summit of a most rewarding journey, the kind that comes upon you unexpectedly, shows you a glimpse of the possibilities, captures your imagination and then keeps you moving until you can see 100 miles in all directions. This particular journey I could not have completed solo. I am indebted to the following people for helping me with various stages along the way.

This work would not have begun without the vision and courage of Ron Dunton. Ron showed me the summit through a pair of binoculars, gave me a faded map, and pointed me in the right direction. The commitment of the Bureau of Land Management, National Office of Fire and Aviation made all the short cuts, backtracking, extra-mileage days, and false summits possible.

I am grateful to Dr. Tim Brown for taking a chance on the idea and making it possible, for his guidance and interpretation of the map, for his insistence on the quality and value of the chosen route. I would like to thank Dr. Paul Tueller for his support of my interdisciplinary approach to a degree in Environmental and Natural Resource Sciences and for his wisdom and perspective on the map, especially those torn corners and folds where the trail was often difficult to follow. I would like to thank Dr. Roger Walker for his insights and thoughtful suggestions to my at-times scary ideas for the ascent.

This journey would not have succeeded without the help of Beth Hall. She taught me more than I thought I could learn about short cuts, known to some as programming. As one who prefers to mosey along all the switchbacks, trying to ascend via short cuts came with its own adventures. More than once Beth grabbed my lifeline when I slipped down the shear face of the FORTRAN Cliffs.

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# Chapter 1 Introduction

## 1.1 Problem Identification

Across the United States (US), the National Fire Danger Rating System (NFDRS) is commonly used to define indices of fire danger rating, which are then used to support many fire management decisions. These decisions are strategic. Fire danger ratings are relative indices designed for 1-2 day temporal and 5,000 – 200,000-hectare spatial scales. Decisions supported by NFDRS include public awareness (e.g. highways signs declaring fire danger conditions), agency staffing and readiness levels, public and industrial activity restrictions and closures, appropriate combinations of suppression resources to dispatch to initiating fires, and the need for additional funding or resources in an area.

The NFDRS of today was developed in the 1970s with one revision in 1988. Technologies of the 21$^{st}$ century are opening up possible directions for new developments in NFDRS. One of the natural directions for NFDRS to evolve is a change in spatial resolution of inputs and ratings from point to grid. To achieve this, the live fuel moisture model within NFDRS will need to be automated. There are two reasons to make this change.

The primary reason is that many advances in spatial data acquisition, computing and display have occurred since NFDRS was made available in the 1970s with manual entry and point data estimates for large areas. Today's remotely located fire weather stations automatically report hourly observations. In the late 1970s most fire weather stations were manually operated and only one hour's observation (1 pm. local time) was collected along with several accumulated daily (maximum, minimum, total) measures. Today, satellite observations of current vegetation conditions are collected in gridded data layers. Meso-scale models produce data layers of forecasted conditions. Geographic Information Systems enable computation of multiple data layers through time and space at higher resolutions than was conceivable 30 years ago. Technology is available to advance the computation and display of NFDRS without compromising the principles and science upon which it was constructed.

The second reason for change is that initiation of the live fuel moisture model each year is not always what it should be. To initiate the live fuel moisture model, the fire manager must declare green-up. Ordinarily this involves making a visual estimate of the live fuel condition in the management area. In many locations, the value of the live fuel moisture model has been compromised by an obligatory declaration according to a calendar date or the springtime increase in staffing.

## 1.2 Objectives

The objectives of this thesis are to address two aspects of the NFDRS live fuel moisture model as follows:

1. Develop an objective, repeatable, and seasonally robust method to determine in "real time" the green-up date at 1-km spatial and 1-week

temporal resolutions using Normalized Difference Vegetation Index (NDVI) from NOAA Advanced Very High Resolution Radar (AVHRR).

2. Develop a process to determine historical green-up dates for historical analysis purposes. Currently, analysis of fire danger using historic data records requires the fire manager to estimate a "normal" green-up date for the entire period of interest. This is due in part because the annual green-up date determined through the years by the fire manager has not been archived. A more accurate portrayal of annual variability of fuel condition would be possible if historical green-up dates were available.

## 1.3 Thesis Content

The approach of this thesis will be as follows:

1. Provide a foundation of background information including a summary of the relevant features of NFDRS, a survey of current green-up practices, and a review of available satellite imagery and its published relationships to vegetation condition.
2. Describe the data applied to the problem, primarily a set of Normalized Difference Vegetation Index measures from 1989-2002.

3. Discuss the methods developed to meet the objectives, in particular the recommended integral method for determining the date of green-up operationally and historically for a pixel.
4. Provide an analysis of the integral method in three locations across the US.
5. Summarize the results and recommend future work that could enable this method to be incorporated into NFDRS “as we know it” and NFDRS of the future.

# Chapter 2 Background

## 2.1 The National Fire Danger Rating System

There are two versions of the National Fire Danger Rating System (NFDRS) currently in use. The 1978 version (Deeming et al. 1977) is a modification of the first national model (Deeming et al. 1972) and is generally best suited for the western US. The 1988 version (Burgan 1988) is a modification of the 1978 version and is designed to improve the model for the eastern US.

An important part of NFDRS is a live fuel moisture algorithm which models change in plant moisture through the growing season. In the 1978 version, the live fuel moisture algorithm categorizes herbaceous fuel moisture stages as pre-green, green-up, transition, cured, and frozen. In the 1988 version, the categories are winter (i.e. pre-green and frozen); spring (green-up), summer (transition), and fall (cured). Because NFDRS generalizes over the ecosystem landscape, these categories are not species-specific phenological stages, but broad statements of the fuel moisture condition for all herbaceous vegetation in the NFDRS fuel model being applied to the area. The live fuel moisture model is not based on "rigorous principles of plant physiology," but it does approximate the moisture content of living herbaceous and woody plants (Bradshaw et al. 1983). The term green-up will be used to represent the 1978 and 1988 concepts of green-up and spring, respectively, for the remainder of this document.

The green-up date in NFDRS is a date that represents the time when a spring flush of growth is generally occurring in the rating area (Burgan 1979). This definition is less than precise, leaving the fire manager with considerable room for interpretation. Schlobohm and Brain (2002) summarize the current consensus guidance for selecting a green-up date:

> Green-up may be signaled at different dates for different fuel models. For any particular model, green-up should be declared when the annual and perennial herbaceous vegetation starts to grow or the leaves of deciduous shrubs begin to appear within the area represented by the fuel model. Green-up should not be started when the first flush of green occurs in the area. Instead, the vegetation that will be the fire problem (represented by the NFDRS fuel model associated with the weather station) when it matures and cures should be identified. Green-up should start when the majority of this vegetation starts to grow.

Note that this explanation of green-up also does not quantify the concept of green-up in easily measured terms.

Declaring the green-up date initiates an increase in herbaceous fuel moisture (FmH) within the live fuel moisture model of NFDRS. Declaring green-up is the “switch” for the live fuel moisture model to begin to mimic the seasonal progression of FmH. While flush with moisture, NFDRS treats the herbaceous fuels as a heat sink that can result in dampened fire danger ratings for some fuel models. As the herbaceous fuels dry out through the course of the season, NFDRS adds them to the dry dead fuels as a heat source.

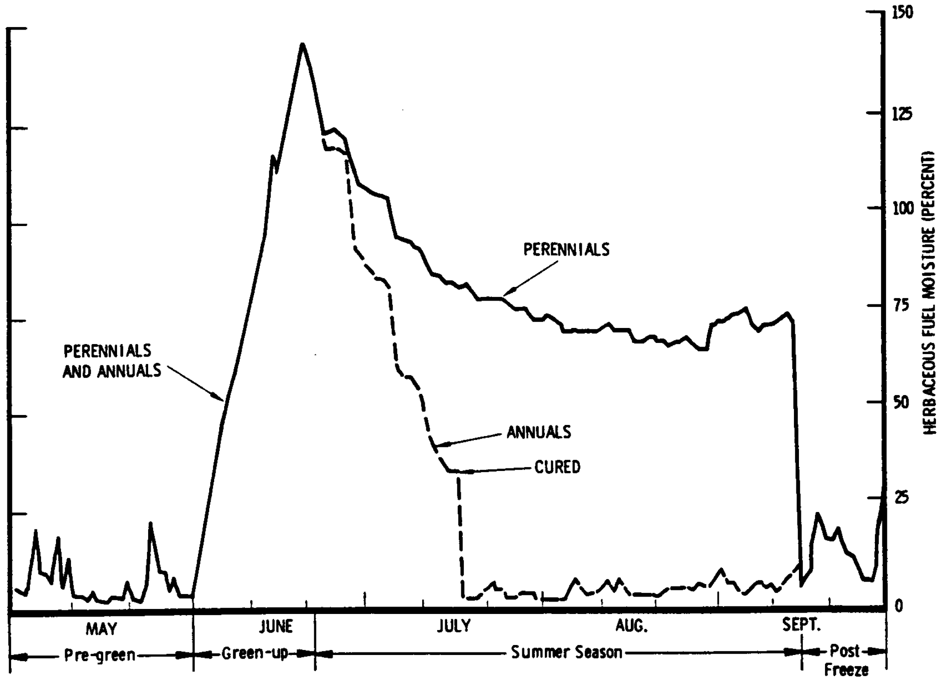


Figure 2-1. Calculated moisture content of annual and perennial herbaceous plants (adapted from Burgan 1979).

A generic example is portrayed in the following set of plots to illustrate the function of the live fuel moisture model. The effect of declaring green-up on modeled FmH is shown in figure 2-1 (adapted from Burgan 1979). Prior to green-up, herbaceous fuel moistures are very low and equal to 1-hour timelag dead fuel moistures. One-hour timelag fuels are dead fuels consisting of herbaceous plants or roundwood less than one-quarter inch in diameter. After the green-up switch is turned on, FmH increases quickly for the duration of the green-up period. The green-up period is a fixed number of days: 7, 14, 21, or 28 days depending on regional climate (Schlobohm and Brain 2002). At the end of the green-up period, herbaceous fuel moistures begin to decline at a rate dependent on whether they are classified as annual or perennial vegetation. The transition stage begins when the FmH drops below 120%. The cured stage begins below 30%. Cured fuel moistures are also modeled as 1-hour timelag dead fuel moistures.

Herbaceous fuel load is transferred between living and dead categories according to FmH as shown in figure 2-2 (Burgan 1979). There are 20 NFDRS fuel models. Each one features a different amount of live and dead fuel loadings that are characteristic of the fuel being modeled (Bradshaw et al. 1983, Burgan 1988). The purpose of declaring green-up is to reflect the contribution of live fuel moisture to fire danger throughout the growing season. As shown in figure 2-3, FmH can vary with green-up date. Depending on factors influencing fuel moisture such as temperature, relative humidity, and precipitation, the timing of turning on the green-up switch affects the magnitude of modeled live fuel moisture. Figure 2-3 shows that a May 27, 1998, green-up date would produce the maximum (250%) FmH before the end of the green-up period. If green-up were declared 4 weeks later, FmH would achieve only 136% before drying begins. Flipping the switch too soon or too late can mean a poorly characterized green-up.

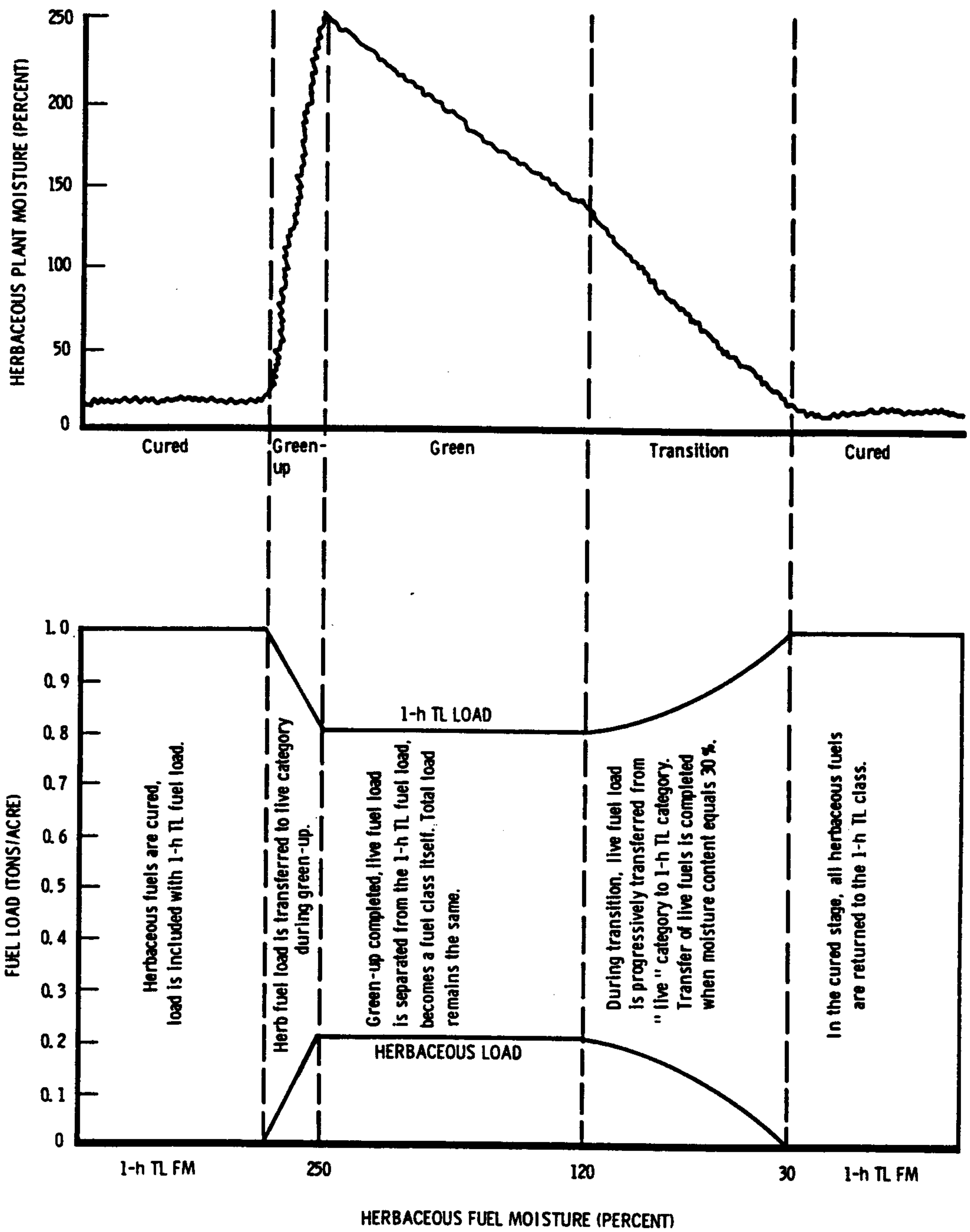


Figure 2-2. Herbaceous fuel load changes between living and 1-hour time-lag fuel categories according to herbaceous moisture content (Burgan 1979).

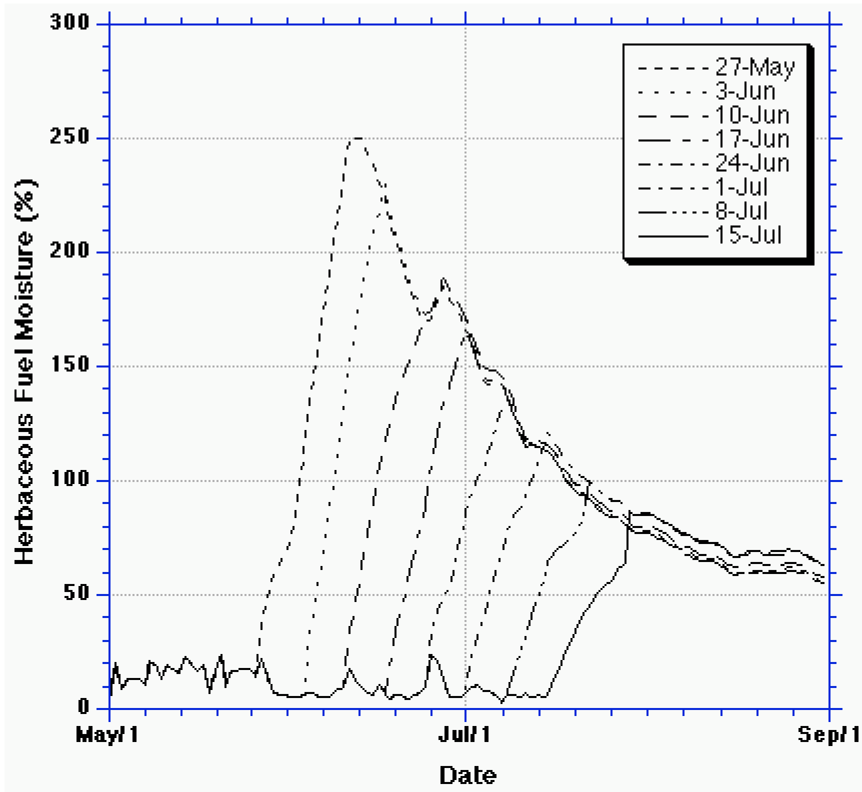


Figure 2-3. Herbaceous fuel moisture trends by 1998 green-up date at Stella station

The impact of FmH on fire danger ratings depends on the fuel model. Figures 2-4 and 2-5 show the relationship between FmH and fire danger ratings at two locations. Stella weather station is located in the forested Cascades of Western Oregon. NFDRS fuel model G (mature conifers) is typically used at this site and fire danger rating is normally derived from the Energy Release Component (ERC). The ERC is a measure of potential heat release of a fire and its computation is primarily a function of large diameter dead fuel moisture. It is not surprising, then, that little connection exists between ERC values and increasing herbaceous fuel moistures (figure 2-4). During the May 1 green-up period, ERC continues to increase, suggesting worsening fire danger, while FmH

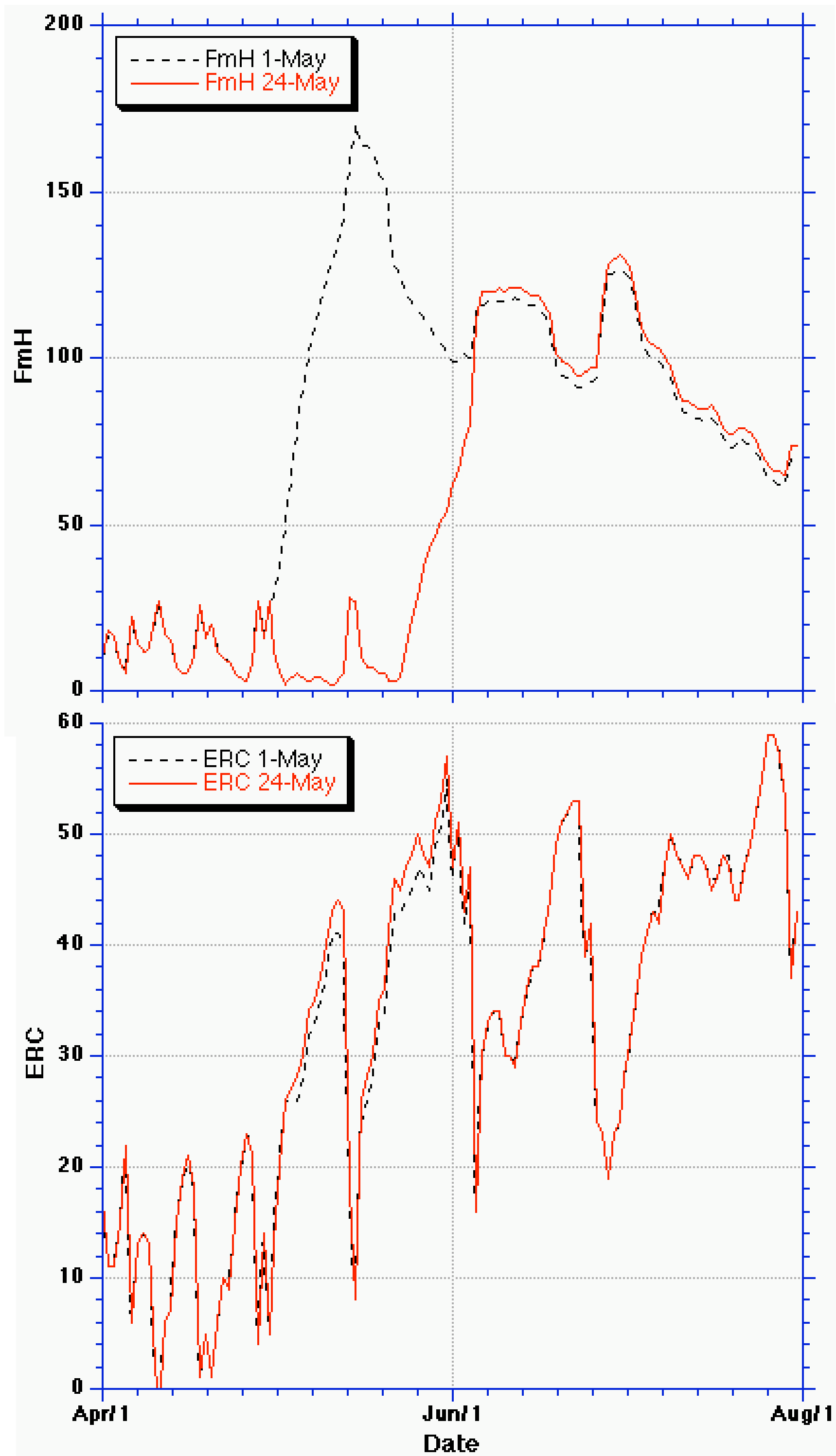


Figure 2-4. Relationship between herbaceous fuel moisture (FmH) and energy release component (ERC) for two 2001 green-up dates at Stella station.

increases. During the May 24 green-up period, ERC remained steady before a brief decrease. The independence of ERC from FmH is evident in the nearly identical ERC traces for both green-up dates.

Brown's Well weather station is located on the sagebrush steppe of Eastern Oregon. NFDRS fuel model T (Sagebrush with annual grass) is typically used at this site and the normal fire danger rating is derived from the Burning Index (BI). The BI is a measure of the potential difficulty of control of a fire. Its computation is a combination of fine fuel, large fuel, and wind influences. Figure 2-5 shows that BI values for fuel model T are influenced by the increasing FmH after green-up. After the April 12 green-up date, once the FmH values increased above the cured threshold of 30%, the BI dropped 73 points and remained near 20 for three weeks while FmH was at its peak. Fire danger was now being significantly dampened. Waiting until May 3 to declare green-up would have resulted in BI values 40-50 points higher, enough to change the decisions fire managers make concerning staffing and resource availability. Alternatively, if the model is not accurately portraying actual conditions, confidence in and use of NFDRS can be threatened.

The determination of green-up date is a subjective decision. Fire personnel who manage the model for their local applications are asked to visually estimate the date when the live fuels of concern have become “flush with growth” over an area that may be tens of thousands of acres in size. As the exploration of 2001 and 2002 green-up dates in section 2.4 will show, the determination of an appropriate green-up date is an awkward task for many fire managers every year.

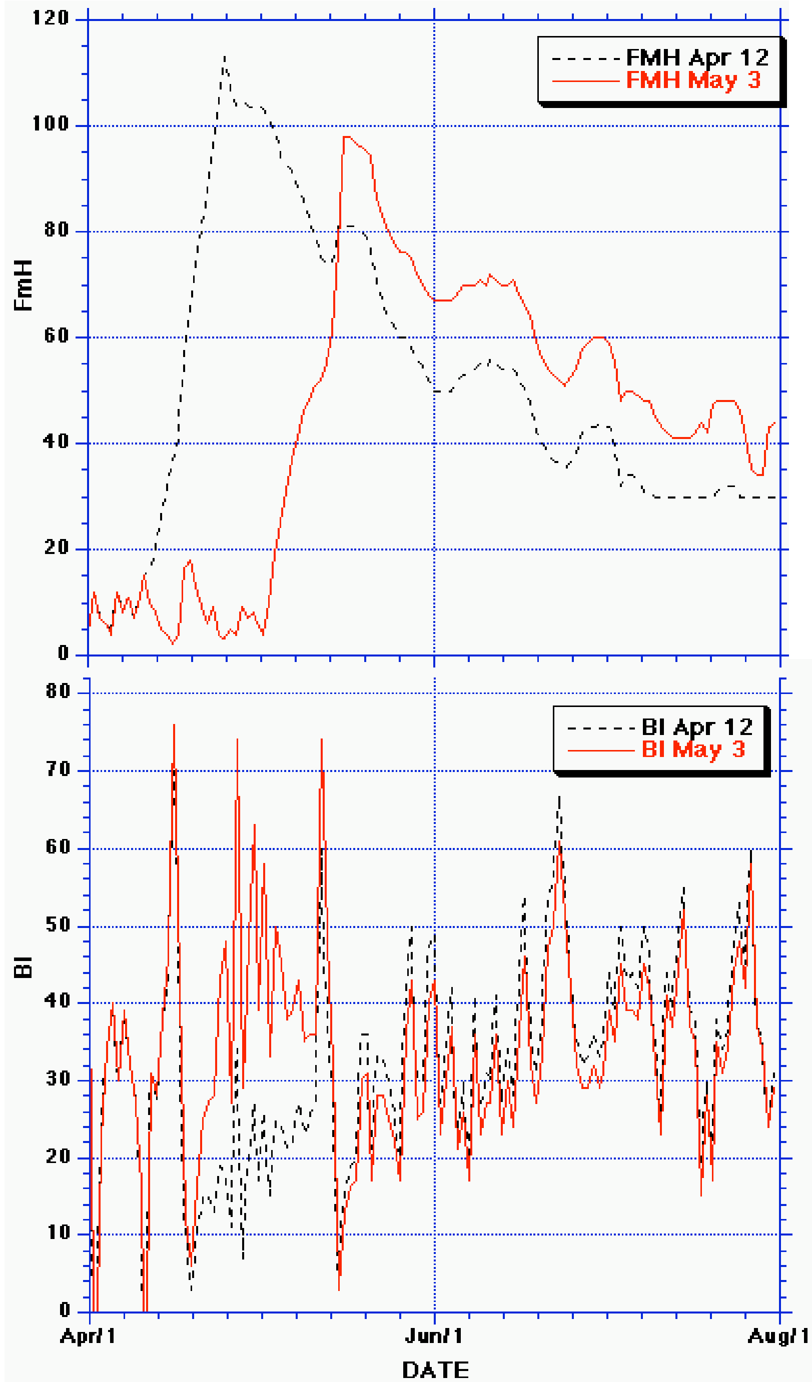


Figure 2-5. Relationship between herbaceous fuel moisture (FmH) and burning index (BI) for two 2001 green-up dates at Brown's Well station.

Upon their determination of a green-up date, fire managers of most federal and many state fire management agencies input this date into a central NFDRS processor, the Weather Information Management System (WIMS). Located in Kansas City at the USDA National Information Technology Center (NITC), WIMS provides daily NFDRS outputs for more than 900 fire weather stations located throughout the US (figure 2-6). WIMS is designed to archive the daily weather observations that would be necessary to conduct an historical analysis of daily fire danger at each weather station. These data are archived in the National Interagency Fire Management Integrated Database (NIFMID), also located at NITC. However, neither WIMS nor the NFDRS processor it replaced in 1992 (AFFIRMS) were programmed to archive the annual green-up date. Thus, no historical records of annual green-up dates exist.

The progression in the live fuel moisture model from green-up to transition and cured is a function of other parameters and estimates, and, although there is equally good reason to consider a role for NDVI in this progression, it will not be investigated here.

The contribution of herbaceous fuel moisture varies among the 20 NFDRS fuel models depending on the vegetation that is modeled. A fuel model is a set of numbers representing the contribution of the dead and live plant material of the rating area. Given the same weather and other inputs to the system, each fuel model will produce different fire danger ratings according to its unique mix of fuel bed components. The 20 models were developed to characterize broad fuel properties found in all 50 states (Deeming et al. 1977). A brief description of each model is provided in Appendix A. A fuel model is not intended to be a perfect match to the local fuel bed conditions, only a reasonable representation for fire danger rating purposes (Schlobohm and Brain 2002).

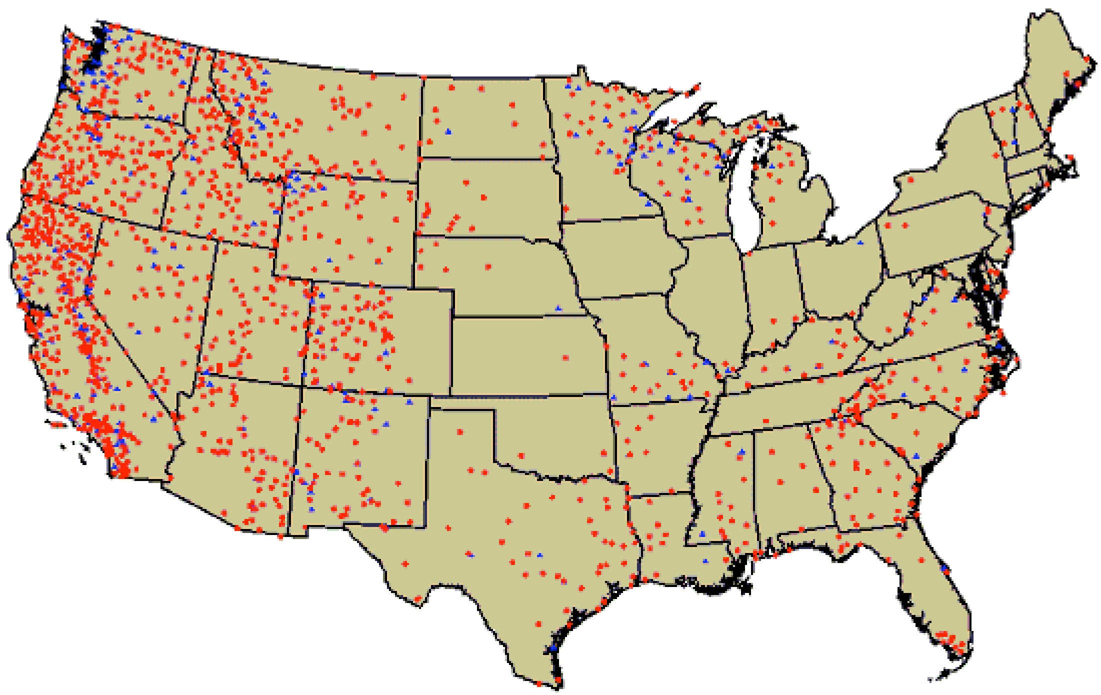

Figure 2-6. NFDRS weather station locations as cataloged in the Weather Information Management System, May 2003 (adapted from USDA Forest Service 2003)

## 2.2 NDVI

Satellite imagery has been studied for monitoring vegetation condition for at least two decades. A concise review of the many satellite-derived vegetation indices is available from Caltech's Division of Geological and Planetary Sciences (http://www.gps.caltech.edu/~arid/analysis/vegindex.html). One form of observation comes from the Advanced Very High Resolution Radiometer

(AVHRR) on the National Oceanic and Atmospheric Administration's (NOAA) polar orbiting weather satellites. The spatial scale of AVHRR data is 1.1 km and it is collected in 5 spectral bands. Bands 1 (Visible red, 0.58-0.68$\mu$m) and 2 (Near-Infrared, 0.72-1.10$\mu$m) are used to develop a Normalized Difference Vegetation Index (NDVI) that is sensitive to the quantity of actively photosynthesizing biomass (Myneni et al. 1992). NDVI is the difference of near-infrared and visible reflectance normalized over total reflectance (Burgan and Hartford 1993):

$$NDVI = \frac{NIR - VIS}{NIR + VIS}, \qquad (1)$$

where NIR is the near infrared spectral measurement and VIS is the visible red spectral measurement.

NOAA satellites provide daily observations of Earth's surface. To reduce effects of atmospheric interference, biweekly composites of maximum NDVI are provided by the Earth Resources Observation Systems (EROS) Data Center (EDC), using a technique first developed by Holben (1986).

The advantages of NDVI data for monitoring vegetation change include complete spatial coverage of earth surfaces, temporal coverage at regular intervals, and a landscape-scale signal that includes current status of all plant species on site. The disadvantages of using NDVI are loss of data due to cloud cover, effects of non-vegetated surfaces, calibration issues between satellites and between sensors, and the complexity of interpreting the data (Schwartz et al. 2002, Huete 1988).

A critical assumption of this thesis is that NDVI observes phenological- or moisture content-related changes in vegetation. This assumption is based primarily on the preponderance of supportive published evidence to this effect, described below. However, exploration of available phenology records and the relevance of phenology to NFDRS green-up resulted in the following reasons why phenology is not part of this analysis:

1. Green-up in NFDRS is not defined in phenological terms; therefore it cannot be quantified in terms of phenology at this time. Phenology records tend to be species-specific, which is not the case for NFDRS fuel models.
2. Phenology records are scarce in many parts of the world (Chen and Pan 2002), have limited spatial coverage (Schwartz et al. 2002), and are not available for fuels of interest to this study in the Western US for the period 1989-2002. For example, Schmidt and Lotan (1980) provide a summary of an extensive phenology study in the Northern Rockies in 1928-1937. A list of locations surveyed and their availability of records is provided in Appendix B.
3. White et al. (1997) argued that comparing phenology to satellite measures is a subjective process. It is not possible to detect the beginning and end of specific phenological metrics.
4. The concept of green-up for NFDRS is more of a low-resolution statement about ecosystem or fuel model seasonal vegetation stage than a high-resolution statement about a particular phenological event. Burgan (1996)

argued that it is not practical to track live vegetation moisture and quantity in detail since it varies greatly across the landscape. For fire danger purposes, all that is required are reasonable estimates. In their discussion of the merits of NDVI, Minor et al. (1999) explained that no prior knowledge of ground conditions is required when analyzing its measurements. Robust objectivity is the desired characteristic of green-up dates in this thesis.

It is generally accepted that NDVI measures phenological change at the broad-scale ecosystem level:

> In two early publications on greenness imagery, Tucker et al. (1983) found NDVI to be closely associated to rainfall events in African grasslands and Goward et al. (1985) suggested that multi-date greenness images can indicate patterns of vegetation growth and senescence.
>
> Justice et al. (1985) developed NDVI time series for various vegetation types and showed that NDVI could establish the timing of green-up (not necessarily the NFDRS concept of green-up), senescence and the length of a growing season. He also stated that since NDVI relates to green-leaf activity, it could be used to monitor vegetation phenology.
>
> In 1986, Holben stratified land cover types by NDVI: 0.002=clouds; 0.025=bare soil; 0.09=light green-leaf vegetation; 0.14=medium green-leaf vegetation; 0.50=dense green-leaf vegetation. Lloyd (1990) suggested that plant growth is unlikely below NDVI of 0.10.

Huete (1988) and Huete et al. (1992) proposed a transform of NDVI to minimize the impact of soil brightness. This technique, called the Soil Adjusted Vegetation Index (SAVI), introduces a constant representing the influences of soil reflectance into the vegetation index computation. SAVI was shown to improve vegetation estimates, especially where soil or rock surfaces are exposed. It is not obvious from the literature why SAVI does not have the popular appeal of NDVI. In order to perform the transform and compute SAVI, it is necessary to obtain the original spectral data: the transformation occurs in the denominator of equation (1). Readily available for this study were the preprocessed NDVI data set from the US Forest Service. The spectral data necessary to compute SAVI values were not readily available. The relative availability of NDVI may contribute to its popularity. SAVI and green-up should be studied to understand what if any differences in management decisions would be made by determining green-up with SAVI instead of NDVI, especially in arid regions.

Lloyd (1989) stated that NDVI records spatial variations in the intensity of photosynthetic activity. He used NDVI to describe the vegetation of the Iberian Peninsula and showed that NDVI time series can distinguish distinct phenology patterns of various vegetation types.

In 1990, Lloyd developed a vegetation classification scheme based on NDVI-derived phenology. He noted a strong relationship between estimates of growing season beginning using climatological data and estimates based on rate of change of multi-date NDVI values.

Working with monthly NDVI composites, Malo and Nicholson (1990) suggested that green-up begins with a sharp increase in NDVI and peaks at time of the maximum NDVI value.

Schwartz and Karl (1990) stated that NDVI would be the best method to measure green-up, but in 1990 there were not enough 1-km data available to meet their needs.

In 1990, Spanner et al. stated that seasonal changes in NDVI are due to phenological changes in leaf area index (LAI) caused by climate, the proportion of surface cover types contributing to overall reflectance, and the solar zenith angle (winter or summer). NDVI discriminates low and higher elevation green-up in the Oregon Cascades. NDVI is well correlated to LAI in western US forests - maximum values occur midsummer, minimum values occur midwinter, a rapid rise occurs in spring and a decrease occurs in fall. NDVI distinguished closed pine stands in western Montana from nearby 50% pine/50% grass mix. These two stands would represent two different NFDRS fuel models: H, healthy closed conifer stand, and C, open pine with grass understory.

Loveland et al. (1991) developed NDVI time series for major vegetation types, based on Lloyd’s (1990) classification. He developed maps for onset of greenness, peak greenness, senescence, and length of growing season, and land cover type maps from, in part, NDVI. Markon et al. (1995) also developed a phenology class map. Burgan et al. (1998) used Loveland’s land cover type map as a foundation for developing the NFDRS fuel model map (Figure 2) (see http://www.fs.fed.us/land/wfas/nfdr_map.htm).

Curran et al. (1992) found that Landsat TM NDVI correlates with seasonal variations in LAI in slash pine in the southeastern United States. Myneni et al. (1992) stated that NDVI could be linearly related to canopy photosynthetic efficiency. Burgan and Hartford (1993) noted that NDVI observes a “vegetation flush” and suggested that it could be used to estimate green-up for NFDRS. Reed et al. (1994) demonstrated that NDVI can “see” inter-annual variability in various US land cover types.

Eidenshink and Haas (1992) identified the historical timing of green-up for the Palouse grasslands, western coniferous forests, and Great Basin rangelands at a multi-pixel scale.

McGwire et al. (1992) characterized phenology patterns through a principal components analysis of NDVI spectral response. They matched their NDVI-derived classification scheme to the CALVEG classification system.

One of the uses of this technology suggested by Burgan and Hartford (1993) and Burgan (1996) is to assess the temporal and spatial extent of vegetation greening and curing in an area. Their suggestions were primarily for the NDVI-derived Visual and Relative Greenness Indexes. The Visual Greenness Index indicates how “green” each NDVI observation is relative to the maximum value NDVI can achieve. The Relative Greenness Index (RGI) measures how green each observation is relative to the historical range of NDVI for the pixel. RGI takes the form

$$RGI = \frac{NDVI - NDVI_{MIN}}{NDVI_{MAX} - NDVI_{MIN}}, \qquad (2)$$

where NDVI is the observation of interest, $NDVI_{min}$ is the climatological minimum and $NDVI_{max}$ is the climatological maximum for the pixel.

In 1994, Reed et al. found that “NDVI offers a means of objectively evaluating phenological characteristics of land cover regions and assessing their variability over large geographic areas.” They linked 12 NDVI-derived metrics to seasonal phenological events. NDVI may not notice the “moment” of a plant’s emergence against a soil background at 1-km resolution, but it will measure the “event” of rapid NDVI increase soon after emergence. Markon et al. (1995) also found that “NDVI measures tend to provide descriptive characteristics of phenological landscape events rather than direct associations with specific plants.” And, the 1-km pixel scale is more appropriate for landscape processes than individual plant communities. This broad-scale capability of NDVI seems highly appropriate for the broad-scale format of NFDRS.

White et al. (1997) argued, “Satellite detection of phenological events is a subjective process”. Absolute beginnings and endings of growing seasons are difficult to identify. The term ‘on-set of greenness’ is used precisely to avoid a direct connection of satellite measures to field measures. Their approach was to design a methodology that would apply across vegetation types. Their method involves a transformation of NDVI based on the daily, annual minimum, and annual maximum NDVI. The relative and broad-scale philosophy of White's approach lines up well with that of NFDRS in general and its green-up herbaceous stage in particular.

Duchemin et al. (1999a) used NDVI to describe temperate forest phenological cycles for deciduous, mixed, and coniferous forest types. A spring signal is noticeable in each, although it is stronger with increasing proportion of deciduous species.

Duchemin et al. (1999b) stated, "NDVI-derived data is useful to monitor the phenological cycle of temperate deciduous forests at a regional scale." They compared ground-based phenology records of temperate forests to NDVI data. NDVI-derived phenology estimates corresponded to ground measures. Results showed differences in budburst between species of deciduous trees at the same latitude. NDVI clearly showed four seasons: low values in winter, rapid incline in spring, maximum values in summer, rapid decline in fall. They compared a growing degree-day model of budburst to the NDVI data and found good agreement.

In 2000, Chen et al. compared NDVI to an extensive phenological record and developed a procedure for determining the season of vegetation growth on a regional scale in China.

Senay and Elliot (2000) compared NDVI to vegetation condition in Oklahoma. They identified onset of greenness, peak greenness and senescence with bi-weekly composite NDVI. All cover types had sufficient signal to differentiate phenology.

In 2001, Chidumayo related observed phenological records on African savannah to average monthly NDVI at 7-km resolution.

Schwartz et al. (2002) continued their exploration of a method to determine the onset of deciduous plant growth. Their approach compared a delayed moving average (DMA) method for NDVI (Reed et al. 1994), a seasonal midpoint NDVI (SMN) method (White et al. 1997, 1999, 2002), a Spring Index method for modeled phenology (Schwartz 1997), and phenology records from the Harvard Forest in Massachusetts.

Reed's DMA method uses a backward looking or delayed moving average value of NDVI to detect rapid change in actual NDVI. NDVI values are compared with the recent trend defined by the DMA. When actual values depart from the DMA a trend change is identified; when the actual values are greater than the trend, this change is declared the start of the growing season (SOS).

White's SMN method has been related to initial leaf expansion of the deciduous forest canopy of New England (White et al. 1997), the Global Observations to Benefit the Environment phenology project (White et al. 1999), and broad leaf forests in France (Bondeau et al. 2000). The SMN method employs a threshold defined as the average seasonal midpoint of NDVI for a data set. The seasonal midpoint is the midpoint between the annual maximum and minimum NDVI values. SOS is defined as the date at which the threshold occurs each year. This method accounts for site-specific NDVI amplitude, but its dependence on a time-constant NDVI threshold makes it vulnerable to time-dependent drift in sensor calibration (Schwartz et al. 2002) and large inter-annual fluctuations in NDVI amplitude.

## 2.3 NFDRS and NDVI

It has been recognized for several years by the interagency fire danger community that the natural evolution of NFDRS is towards computation and display with higher spatial resolution (Burgan 1996, Burgan et al. 1997). Currently, computations of NFDRS outputs are made as point data at the location of the weather station used to collect the weather input data. These point data are often collected and, appropriately weighted, combined to provide a single fire danger rating for a larger area represented by several neighboring weather stations, such as a fire danger rating area.

Fire danger rating areas are defined subunits in a management area that are generally uniform in fuel model, climatology, and topography (Fosberg and Furman 1971). Fire danger rating areas give spatial context to point data. They are the location on the ground to which the computed fire danger ratings apply. One example of this computation and display is shown in figure 2-7. This is a map of hourly fire danger for each fire danger rating area in California created by the Program for Climate, Ecosystem and Fire Applications and displayed at http://www.cefa.dri.edu/HourlyFD/.

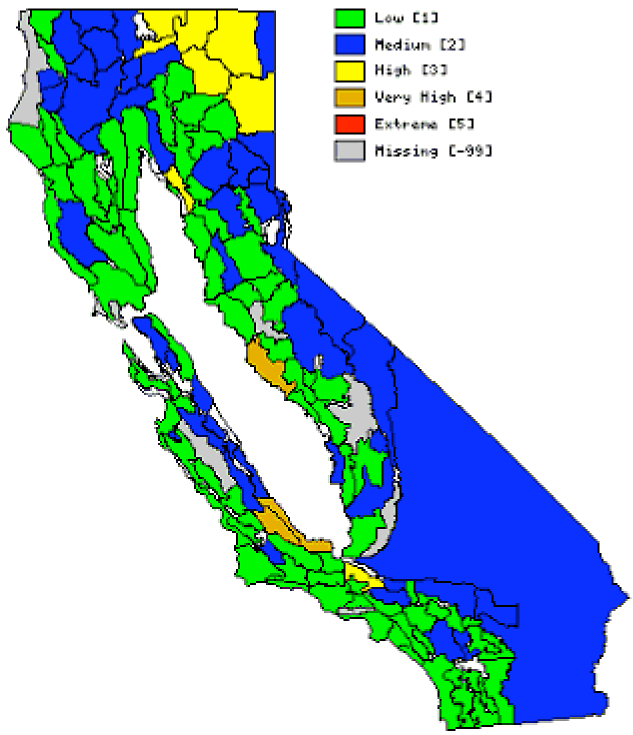


Figure 2-7. Example of application of Fire Danger Rating Areas: Experimental Hourly Fire Danger in California, 1940 Hours PST, May 23, 2003.

Also, these point data are being used to create a national map of adjective fire danger rating as part of the USDA Forest Service's Wildland Fire Assessment System (figure 2-8). This map is displayed at http://www.fs.fed.us/land/wfas/fd_class.gif. The spatial information on this map is developed using an inverse-distance squared algorithm (Burgan et al. 1997). Developed in 1994, these maps were the first national-scale spatial presentation of daily fire danger. The daily fire danger display is based on only those weather stations for which all necessary data was received by WIMS. This display technique does not account for topography. Clearly, information not in proximity to a weather station is of questionable accuracy and value. Nevertheless, this display of fire danger at a national scale is influencing the evolution of fire danger rating.

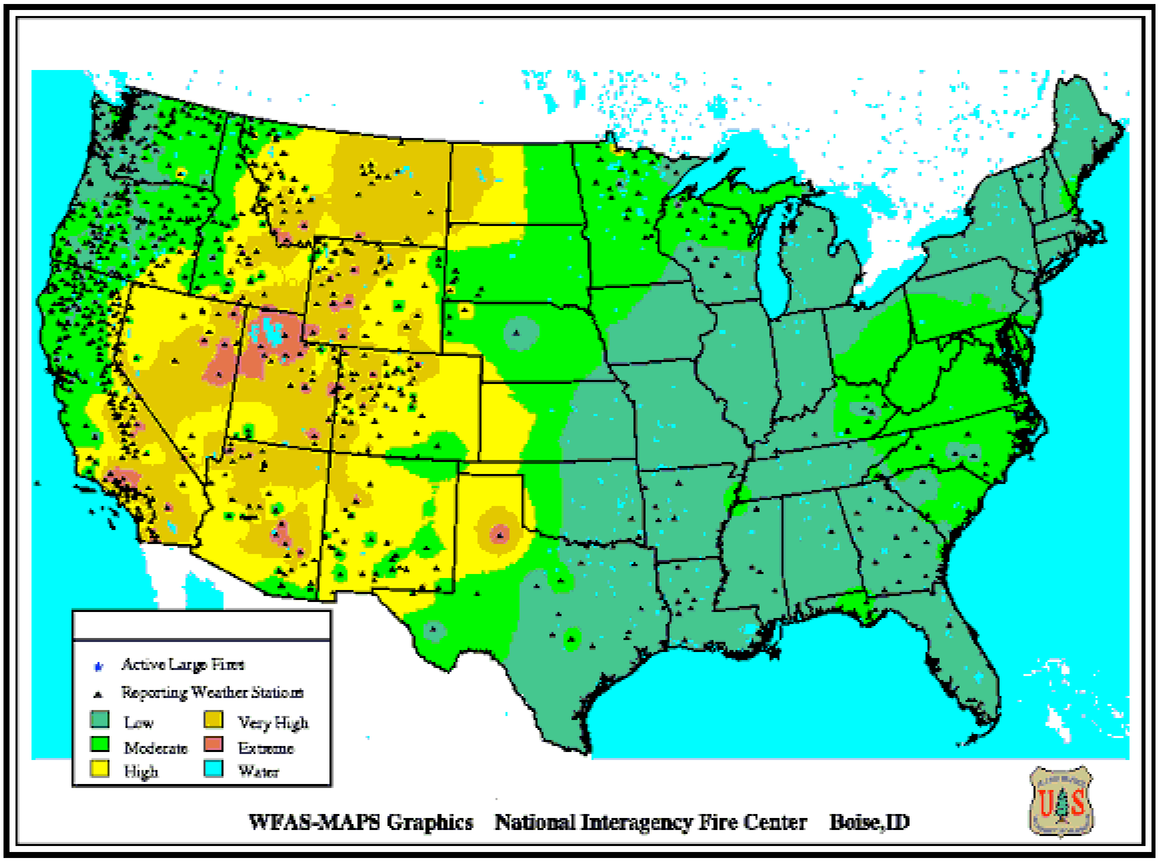


Figure 2-8. Example of a national map of observed adjective fire danger. Display, for September 27, 2001, is based on reporting stations only. Adapted from USDA Forest Service (2003).

To begin to improve upon the spatial resolution of NFDRS outputs, Burgan et al. (1998) developed a 1-km scale NFDRS fuel model map. This new GIS data layer was intended to be the spatial representation of fuel models for the computation of "next-generation" fire danger ratings. Burgan et al. (1998) assigned NFDRS fuel models to each 1-km pixel of the contiguous US by applying the NDVI-derived 1-km land cover characteristics database of Loveland et al. (1991) and Omernick's (1987) ecoregions.

Analysis of NDVI at the spatial scale of 1-km is considered appropriate for describing landscape-scale phenological events in ecosystems as opposed to that of individual species (Markon et al. 1995, White et al. 1997). Landscape-scale measures and ratings are precisely the context of fire danger rating.

In 1998, Burgan et al. proposed a simplified fire danger rating computation called the Fire Potential Index (FPI) to take advantage of the new spatial analysis of fire danger provided by the 1-km NFDRS fuel model map and data layer. FPI is computed for each 1-km pixel based on the fuel model, the Relative Greenness (RG), and the 10-hour time-lag fuel moisture (which is computed spatially in WFAS as described above for adjective fire danger). Of significance to this study is Burgan's approach to the NFDRS concept of green-up. RGI is used as a surrogate for the live fuel moisture model in the NFDRS. There is no declaration of green-up. Instead, the value of RGI is used to determine the fraction of live fuel load for the fuel model that is a heat sink - the "green" fraction – and the fraction that is a heat source – the "cured" fraction.

Burgan's approach, where the live fuel moisture model is replaced entirely by RG, is intriguing for its simplicity. The dependence of RGI on long-term maximum and minimum NDVI values may weaken its portrayal of live fuel moisture in vegetation types whose $NDVI_{max}$ and $NDVI_{min}$ are highly variable through time (White et al. 1997). In the field, the FPI has received limited acceptance as a replacement to conventional NFDRS. By contrast, the objective of this study is simply to use NDVI in near-real time to identify the often-intangible green-up date and to leave the NFDRS live fuel moisture model otherwise intact and functioning. To do this, a blend of both Burgan's and White's techniques will be developed.

Burgan chose to employ the NDVI-derived RGI as the indicator of fuel moisture. Here, the "raw" NDVI measure is employed 1) in order to begin this analysis with a baseline, rather than a derived, measure, and 2) because of the wealth of research connecting landscape-scale vegetation growth to NDVI.

The advent of fire management applications for Geographic Information Systems (GIS) and remote sensing products in the last 10 years is also contributing to the evolution of fire danger rating. For example, the Oklahoma Fire Danger Model (Carlson et al. 1996) produces daily fire danger indices over the state of Oklahoma using hourly weather from 110 automated weather stations located throughout the state, 1-km NFDRS fuel model map, weekly 1-km RGI, and dead fuel moistures modified slightly from the 1988 version of NFDRS (figure 2-9).

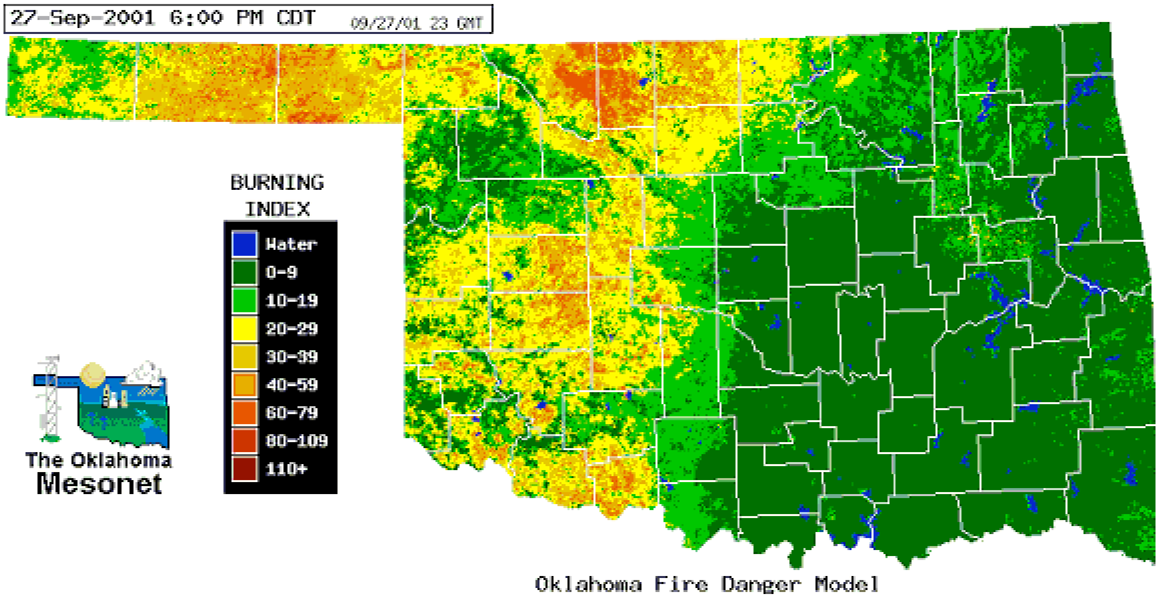


Figure 2-9. Example of Oklahoma Fire Danger map.

Implementing gridded weather products is expected to be a significant part of computing the next phase of “next-generation” NFDRS. This would provide, for example, a forecast for tomorrow’s fire danger on a gridded map product. This product might be based on state-of-the-art operational weather forecast models, which account for topography, the 1-km fuel model data layer, and live fuel moisture derived from NDVI-derived greenness. The Fire Behavior Research Work Unit at the USDA Forest Service Missoula Fire Sciences Lab and the Missoula Forecast Office of the National Weather Service is producing one example of such a product experimentally. Their product is available at http://www.fs.fed.us/land/wfas/wfas26.html. Unlike the FPI, this product is computed with NFDRS-modeled large (100- and 1000-hour timelag) dead fuel moisture. Another source of these types of products that is now under development is the Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS, http://www.fs.fed.us/fcamms/).

### 2.4 Green-up Dates

To assess the quality of green-up declarations by fire managers, a coarse review of green-up dates entered into WIMS for 923 NFDRS weather stations was conducted for 2001 and 2002. This is possible because WIMS retains the current green-up date until a new one replaces that date. Green-up dates were collected from late spring to mid-summer in both years. The weather stations sampled were all the remote automatic weather stations in WIMS for the following states: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, North Carolina, Oregon, Texas, Washington, and Wyoming. These included federal, state, and local government operated stations. For each station, only the green-up date for the primary fuel model was evaluated.

The ideal status of these green-up dates would be for each date to reflect the spring conditions of the herbaceous fuels in the areas represented by each weather station. In other words, each green-up date would be unique with respect to the previous year and to its neighboring stations. Activation of the green-up date would appear to have initiated the live fuel moisture model (which can be verified by the herbaceous fuel moisture value). The date chosen would be logical with respect to time and the subsequent modeled dates of transition and cured. This ideal status appeared to be the case for 564 or 61 percent of the stations surveyed.

The remaining 359, or 39 percent, of the stations were experiencing one or more of the green-up issues listed in Table 2-1. A complete list of these issues by station can be found in Appendix C. A total of 580 instances of green-up issues were tallied from these 359 stations.

| Category | Green-up Issue |
|---|---|
| 1 | Green-up date is identical to neighbor station(s) |
| 2 | 2002 green-up date is identical to 2001 green-up date |
| 3 | No entry or logical date set well after actual event |
| 4 | Herbaceous stage is not logical |
| 5 | Herbaceous stage is not functioning |

Table 2-1. Green-up issues by category

The Category 1 green-up issue occurs when neighboring stations are assigned identical green-up dates. This is done primarily out of convenience by the local manager. However, modeling fire danger in time and space may suffer as stations representing widely disparate elevation, fuels, and weather conditions end up with the same green-up date. For example, in California, Corning (#040814) station, located at 294 feet elevation, receiving 20 inches of annual precipitation, representing fuel model A, was given the same 2002 green-up date (April 15) as Lassen Lodge (#040815) station, 4000 feet, 40 inches, fuel model C, and Thomes Creek (#040816) station, 1040 feet, 19 inches, fuel model F. In Oregon, Wagontire (#353512) station, 6510 feet, 11.4 inches, fuel model T, on a ridge/peak location was given the same green-up dates in 2001 (May 15) and 2002 (May 22) as nearby Crow Flat (#353515) station, 5130 feet, 15 inches, fuel model C on a valley bottom location. Of the 580 green-up issue events, 23 percent of them were for Category 1.

Category 2 is a situation in which the same calendar date is used every year for green-up. This is another convenience option for the user and it may coincide with increased seasonal staffing to perform the operation. This situation shows no regard for annual climate fluctuations and their impact on portraying fire danger in the early part of the fire season. Examples of stations in this category and their 2001/2002 green-up dates are Lodgepole (#101044), May 24, Red Box (#350718) May 19, and Big Creek Baldy (#240119), May 15. Category 2 represents 3 percent of the green-up issue events.

Category 3 occurs either when no green-up date was entered or when it was entered several weeks after the entry date suggests it took place. Both of these events mean that during the springtime green-up period, fire managers did not have an appropriate representation of fire danger. Instead, NFDRS would have overestimated fire danger for the period by continuing the assumption that, without green-up, the herbaceous fuels are behaving like dead fuels and contribute to fire danger as a heat source rather than a heat sink. As of June 3, 2002, Minam station in Oregon (#341416) at 3600 feet elevation was still in pre-green status. As of June 6, 2002, Square Butte station in Montana (#242404) was showing a current herbaceous stage as transition dated May 5, 2001. Thirty-two percent of the green-up issue events are attributed to this category.

Category 4 is a situation when the current herbaceous stage does not make sense according to how the live fuel moisture model works. For example, in May 2002, Carpenter Ridge (#041213) station was showing the green-up date to be April 1, 2002, but it also showed the cured date to be April 1, 2002. The only way these two dates could be identical is if the local users attempted to override the model and force curing simultaneous to green-up. If the model were allowed to run its course, cured herbaceous stage would occur more than a week following green-up at the earliest. This and other similar situations make up this category and are indicative of the users not fully understanding how the live fuel moisture model operates within NFDRS. This category represents 22 percent of the green-up issues recorded.

Category 5 occurs when the herbaceous stage, such as green-up, transition or cured, is incorrectly registered in the WIMS processor. This category includes two types of situations involving the herbaceous stage. First, and most common, an appropriate green-up date may have been determined, but idiosyncrasies within WIMS make it possible for the manager to edit the green-up date without the “switch” going on for the live fuel moisture model. For example, on May 22, 2002, the Vandenberg station in California (#045219) catalog record showed that green-up had been declared on April 15, 2002, and, suspiciously, that the herbaceous stage, 5 weeks later, was still green, meaning herbaceous fuel moisture would be, by definition, above 120%. However, the herbaceous fuel moisture on May 22 was actually 30%, meaning the herbaceous stage should have switched automatically through transition to cured.

The second situation happens when green-up is declared again by the user after the model has progressed through the transition or cured stage but it does not take effect. For example, in June 2002, Dead Indian Ridge (#101402) station was showing a transition date of May 26, 2002, and a new green-up date of May 30, 2002, but the herbaceous fuel moisture was down into the cured range at 13%. While this issue is not a direct result of failure to recognize the appropriate timing of green-up, it is a common problem of manual green-up date entry and leads to dissatisfaction with the green-up process of NFDRS. Category 6 events represent 20 percent of the green-up issue events identified.

These five green-up issues support the concept of utilizing an automated green-up process in NFDRS. Such a process would be able to identify and implement unique green-up dates for each fire weather station or rating area and each associated fuel model, for each year and season of the year, and in a timely manner.

# Chapter 3 Data

## 3.1 NDVI Data

The primary source of data for this project is a January 1989 to August 2002 NDVI data set initially developed from spectral data by EROS Data Center (EDC) and then further processed into 1-week composites by the US Forest Service Intermountain Fire Sciences Lab in Missoula. The original (1989-2001) dataset (Burgan et al. 1999) was reconfigured during Summer 2002 to standardize the entire period of record.

This is a dataset of 1-week maximum composites for the contiguous 48 United States and portions of Canada and Mexico. The image date corresponds to the last day of the composite period, as shown in Appendix D. There are 52 composite periods in each year, set up to enable inter-annual analysis of each period. (During 1990, 1996, and 2001, a 53rd period occurs; it is averaged into the 52nd period.) The dataset has been corrected for atmospheric interference resulting in higher maximum NDVI values than Burgan's original data set (Bartlette 2003). The fractional values of NDVI have been transformed to values between 100 and 200 by the formula:

$$NDVI_{transform} = (NDVI_{fraction} \cdot 100) + 100 . \qquad (3)$$

In this way, NDVI expressed as 0.60 becomes 160. NDVI values less than 103 are considered non-vegetated. Clouds and snow are value 0 and are effectively missing values. Data for some periods are missing or questionable, due to satellite or processing issues. In this study, all values marked in Appendix D as missing, peculiar, or not cloud screened, and all values less than 103 are treated as missing. A time series for the period of record for the central pixel in each of three 3x3 pixel study areas is shown in figures 3-1, 3-2, 3-3.

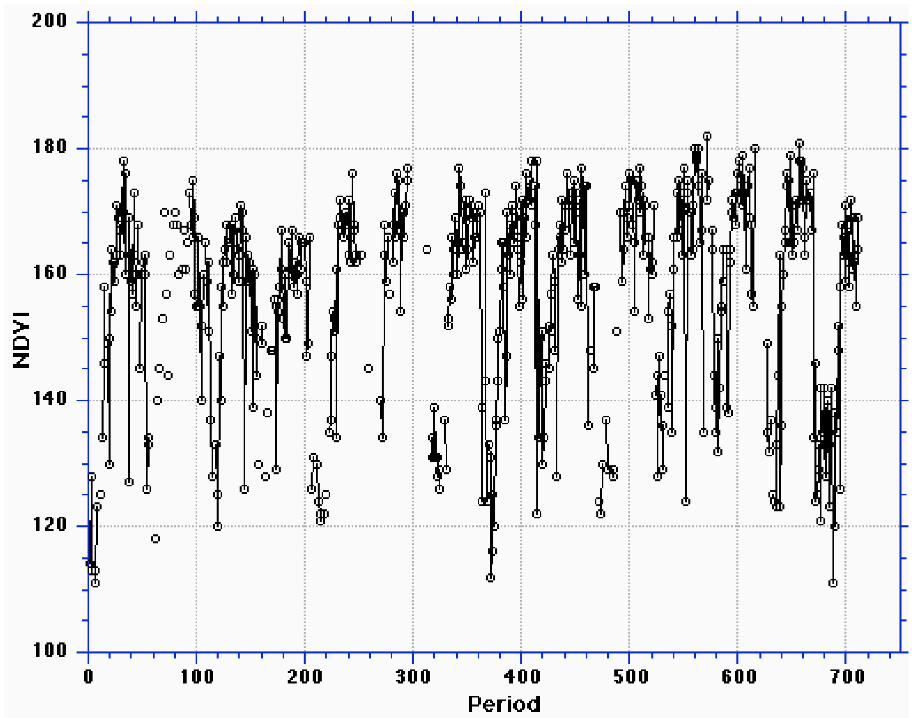


Figure 3-1. NDVI time series, period of record (January 1989 – August 2002), for central pixel of California study area.

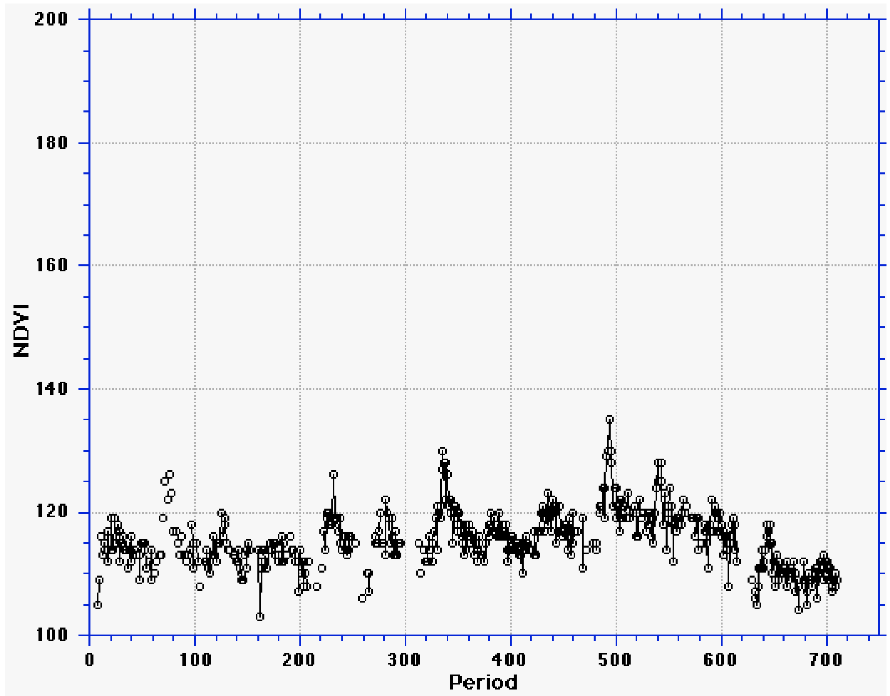


Figure 3-2. NDVI time series, period of record (January 1989 – August 2002), for central pixel of Nevada study area.

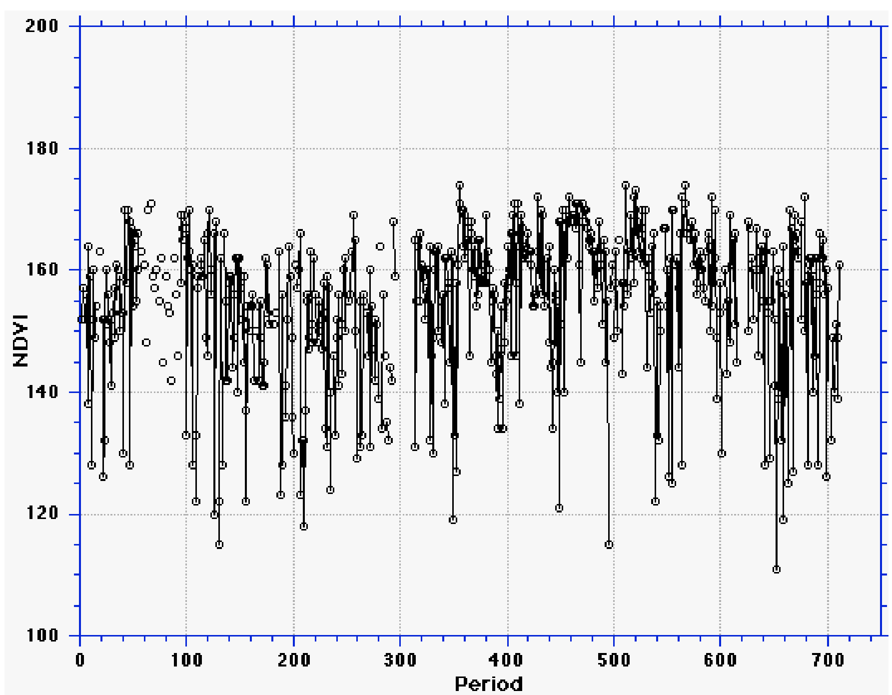


Figure 3-3. NDVI time series, period of record (January 1989 – August 2002), for central pixel of Florida study area.

Other spatial scales of satellite imagery, such as 30-m Modis imagery, are available, and the proposed method could apply to them, but there are two reasons for applying 1-km resolution data to this study. First, the 1-km resolution of AVHRR imagery is generally accepted in the literature for ecosystem-scale applications. This spatial scale fits the low-resolution spatial scale of NFDRS. Greater detail is not required to develop a fire danger index. Second, 1 km is the spatial scale the fire danger practitioners are most familiar with today. Map products of greenness imagery (Burgan and Hartford 1993) and “Next-generation fire danger” from the Oklahoma mesonet (Carlson et al. 1996) are available at this scale.

Many of the applications of NDVI reviewed earlier involved monthly composite imagery. More recently, 2-week composite imagery has been available. In order to track the drying trends of fire-prone vegetation, the US Forest Service Intermountain Fire Sciences Lab in Missoula has been processing 1-week composites of NDVI for the contiguous 48 states. The advantage is that vegetation change is potentially measured more frequently. Weekly information is frequent enough to become part of strategic decisions regarding fire personnel and resource deployment during a fire season in the US, whereas, monthly and bi-weekly is not. The disadvantage of 1-week time-scale is that cloud cover may obscure more portions of the map.

The 1-week time-scale is appropriate for determining green-up dates for fire danger rating because more precision generally has minimal impact on future fire danger ratings and the decisions based on them. A broad-scale statement about the general growth stage of the predominant vegetation in an area should be on a relatively coarse time-scale. A weekly time-scale is already part of the live fuel moisture model of NFDRS. The length of time a rating area remains in green-up status after the declaration of green-up is 1, 2, 3, or 4 weeks depending on the general climate of the area.

One of the tools used to explore and manipulate this dataset is the United Nations/US Forest Service/US Geological Survey-sponsored public domain software program WINDISP 4 (Pfirman et al. 1999). WINDISP 4 provides display and analysis of time series satellite imagery. WINDISP 4 was used to locate pixels geographically and by fuel model (using the NFDRS fuel model map) and to develop analysis categories of pixels based on the normal range of NDVI values.

Climatological NDVI values for each 52 annual periods (weeks) of the year were computed for individual pixels to define a feature of the proposed method based on the pixel’s historical NDVI record. This was done in two ways. The first method was developed for data analysis purposes using custom programming code (see Appendix E). The second method was done using WINDISP 4 to develop a visual display of the spatial and temporal trends in climatological “greenness” across the conterminous US. Both methods computed the average NDVI value for each period from the period of record.

## 3.2 Pixel Classification

Three approaches are made to classify pixels into logical vegetative groups. The purpose of classifying is to determine whether or not a process for defining green-up dates can be generalized for presumably similar pixels. If so, this would very likely simplify determination of the green-up date over large areas, display of the current green-up status, and implementation of the green-up date in NFDRS.

### 3.2.1 NFDRS Fuel Model Map

A NFDRS fuel model data layer is provided by Burgan's 1 km NFDRS fuel model map. This dataset was developed from Loveland's NDVI-derived land cover classification, as noted earlier, and from on-the-ground verification and local fire manager input. This data layer consists of 16 NFDRS fuel models as well as water, agricultural, barren and marsh areas (see Figure 3-4). Only 16 of the 20 NFDRS fuel models are displayed because 3 fuel models are for slash or cut woody material and 1 fuel model (E) is the wintertime version of the eastern deciduous forest fuel model (R). Slash models have no live fuel component and are temporary in nature. They will not be included in this study.

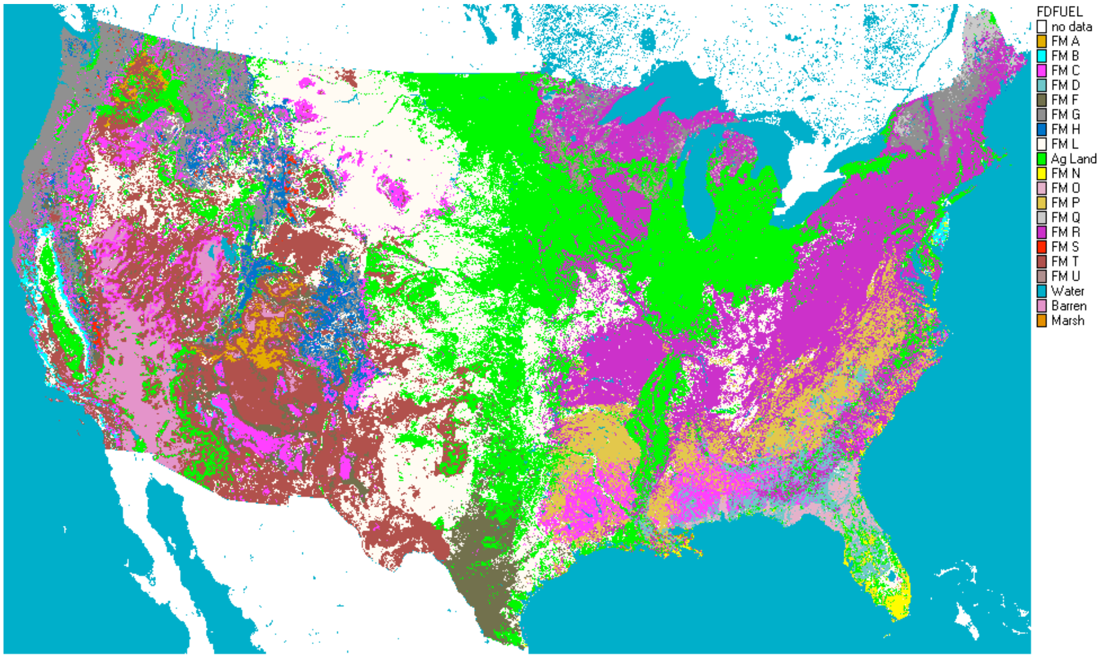


Figure 3-4. 1-km NFDRS fuel model map (Burgan et al. 1998, USDA Forest Service 2003)

### 3.2.2 Current Condition Cover Types

Current condition cover type data was obtained from the US Forest Service website for “Coarse-scale spatial data for wildland fire and fuel management”: http://www.fs.fed.us/fire/fuelman/. The current cover type data layer depicts the vegetative cover types present across the conterminous US as of 2000. These data are derived from Loveland’s (1990) land cover classification and the 1992 Resources Planning Act map of Forest Types of the United States developed by the Southern Research Station, USDA Forest Service. Classifications of potential vegetation and historic fire regimes were then combined with local knowledge to produce the current cover type data layer (Schmidt et al. 2002). Cover type classifications may be more applicable to ecology than to fire, but were used in this study to discuss variation in the fuel model classifications and to explain the concept of difference bins.

### 3.2.3 NDVI Difference Bins

A pixel classification of difference bins was developed (figure 3-5) using WINDISP 4. This classification scheme groups together in “difference bins” pixels whose climatological maximum and minimum NDVI differ by the same amount. For example, pixels whose climatological maximum is 128 and minimum is 120 are placed in difference bin 8. There is relatively small change throughout the year in NDVI signal at these pixels. Pixels with a maximum of 170 and a minimum of 110 are classified into difference bin 60. Pixels in this category experience relatively large intra-annual change in NDVI signal. This procedure allows pixels to be grouped according to the amplitude of their NDVI annual signal, rather than by a description of the vegetation or fuels on site. There are 45 even-numbered difference bins from 0-90 populated by pixel counts as shown in Figure 3-6. These bins are even-numbered because in WINDISP 4 the translation from pixel color value to NDVI value is:

$$NDVI_{value} = ((Pixel_{value}) \square 2) \square 256 . \qquad (4)$$

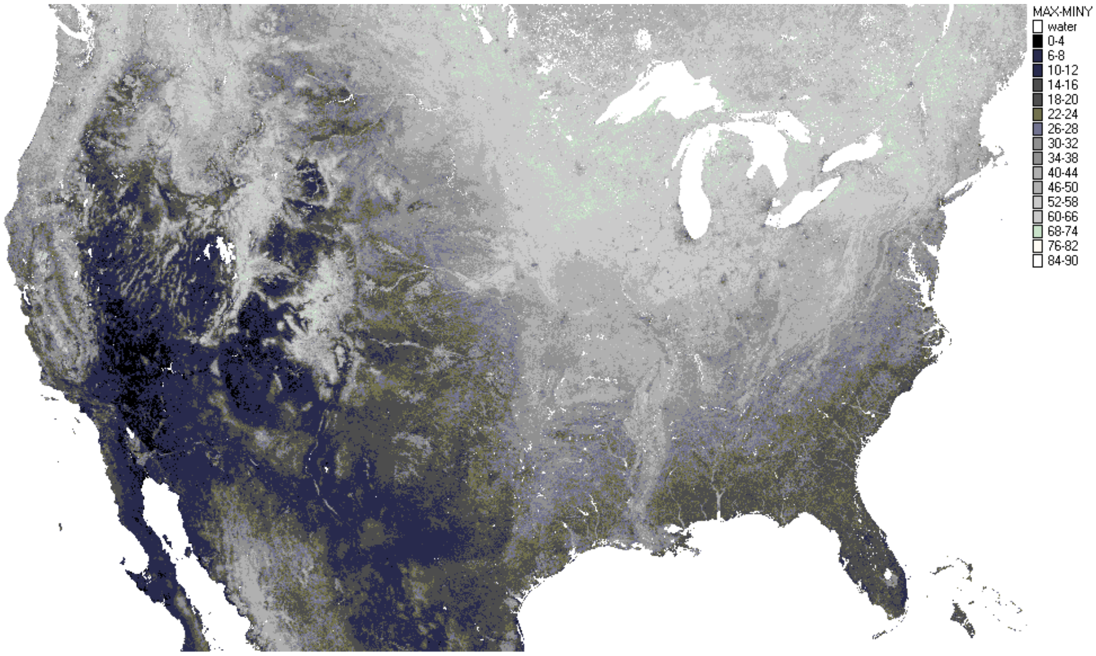


Figure 3-5. 1-km pixels classified by difference bin.

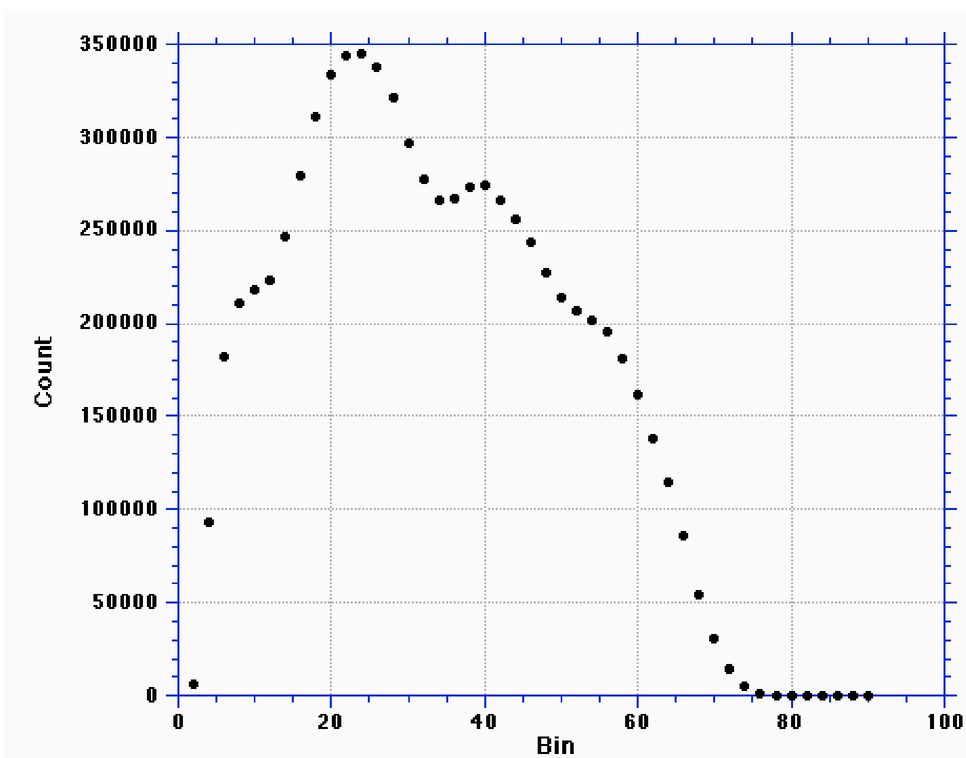


Figure 3-6. Distribution of difference bin counts for pixels in figure 3-5.

## 3.3 Study Locations

### 3.3.1 Initial Exploration

The initial analysis of NDVI time series was performed by NFDRS fuel model category at two different test sites in Oregon (Figure 3-7). Pixels were identified by NFDRS fuel models in order to assess whether these conventional NFDRS descriptions of vegetation would be appropriate with respect to NDVI and the proposed method. The two locations were chosen because

1) They represent two common, yet extremely different western US NFDRS fuel models,
2) They are about 180 km apart at effectively the same latitude (42.99 and 43.33$^{o}$N latitude).

One test site represented the conventional NFDRS fuel model G and will be called the Fuel Model G site. It was located in the northwest corner of Crater Lake National Park. The second test site represented the conventional NFDRS fuel model T and will be called the Fuel Model T site. It was located west of Burns, Oregon. Each test site consisted of 4 pixels arranged in a 2 x 2 configuration, located away from developed areas.

The nearest NFDRS fire weather station was located for each test site. These Remote Automated Weather Stations (RAWS) measure the weather that would be used today to determine fire danger in and around the test sites. Fire manager estimates for green-up date would appear on the station catalogs in WIMS for these stations. Archived weather data was retrieved from NIFMID for these stations. Stella station (located on the Rogue River National Forest west of

Crater Lake National Park at –122° Long. /42° Lat.) was closest to the fuel model G site and Brown's Well station (located on the Burns District of the Bureau of Land Management south of Hampton, Oregon, at –120° Long. /44° Lat) was near the fuel model T site.

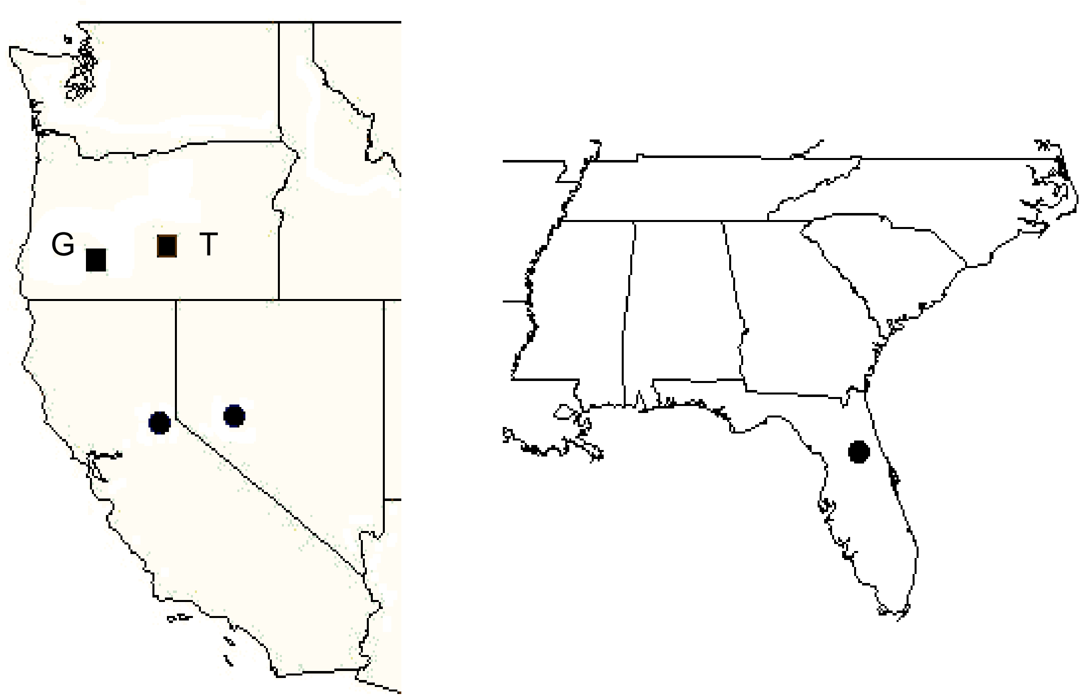


Figure 3-7. Locations of test sites in Oregon (squares) and study areas in California, Nevada, and Florida (circles).

3.3.2 Study Areas

Three study areas were selected to demonstrate the application of the methods and their general locations are depicted by the circles in figure 3-7. Each location consists of 9 pixels in a 3x3 grid. The sites were chosen to represent the 2 peaks in the frequency distribution for the difference bins (20 and 40) (figure 3-5) and one difference bin (10) typical of sparsely vegetated areas. Study area 1 is located in California on the El Dorado National Forest at 1500 meters elevation. Its central pixel is located at Longitude -120.43/Latitude 38.89, west of Union Valley Reservoir. It is representative of the mixed conifer forests of the western slopes of the Sierra Nevada range. The classifications for this site for NFDRS fuel model, cover type, and difference bin are fuel model G, Douglas-fir, and 40, respectively. Case Study Area 2 is located in Nevada on the Carson City District, Bureau of Land Management, at Longitude -118.32/Latitude 39.05, south of Big Kosock Mountain, adjacent to State Route 839. It is representative of pinyon-juniper woodland. The classifications for this site are fuel model C, desert shrub, and 12, respectively. Location 3 is located in Florida on the Ocala National Forest at Longitude -81.70/Latitude 29.16. It is representative of southern rough or pine stands with palmetto/gallberry understory. The classifications for this site are fuel model D, longleaf slash pine, and 20, respectively. The fuel model and difference bin classifications of all 9 pixels at each location are shown in table 3-1.

| **California** | | | | | | **Nevada** | | | | | | **Florida** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G | 40 | G | 40 | G | 42 | C | 10 | C | 10 | C | 10 | D | 24 | O | 22 | O | 22 |
| G | 36 | G | 40 | G | 40 | C | 10 | C | 12 | C | 10 | D | 22 | D | 20 | D | 20 |
| H | 36 | G | 36 | F | 42 | C | 10 | C | 10 | C | 10 | D | 22 | D | 20 | D | 18 |

Table 3-1. Fuel model and difference bins for each pixel at 3 study areas.

# Chapter 4 Methods

## 4.1 Introduction

Given the wealth of published NDVI and vegetation relationships, the objective here is to find an approach that fits the low resolution of NFDRS and meets the performance requirements of an operational system. Malo and Nicholson (1990), Loveland et al. (1991), Reed et al. (1994), White et al. (1997), Duchemin et al. (1999b), and Chen et al. (2000) defined green-up for their purposes (start of season, onset of greenness, etc.) as a rapid increase in NDVI. Wade et al. (1994) and Senay and Elliot (2000) used a differencing approach. Markon et al. (1995) and Goldman and Verbyla (1998) suggested green-up thresholds.

Figure 4-1 shows a smoothed trend in NDVI for the entire 728-week time series of one pixel in the Fuel Model T test site of central Oregon. The inter-annual variability demonstrates the difficulty of either an NDVI or calendar date threshold for green-up at this location. A calendar date threshold of April 1 would occur arbitrarily somewhere along the annual Spring increase of NDVI, at times near the beginning (period 480), the middle (120), and the end (370). A threshold of a fixed number of periods (17 in this example) after the minimum would occur near the beginning (period 110), the middle (360), the end (340); beyond the maximum (650), and before and after the April 1 date. A threshold of NDVI value, such as 120, would be higher than the annual maximum (period

180), lower than the annual minimum (410), and near the beginning, middle, and end of the spring increase of NDVI values during other years.

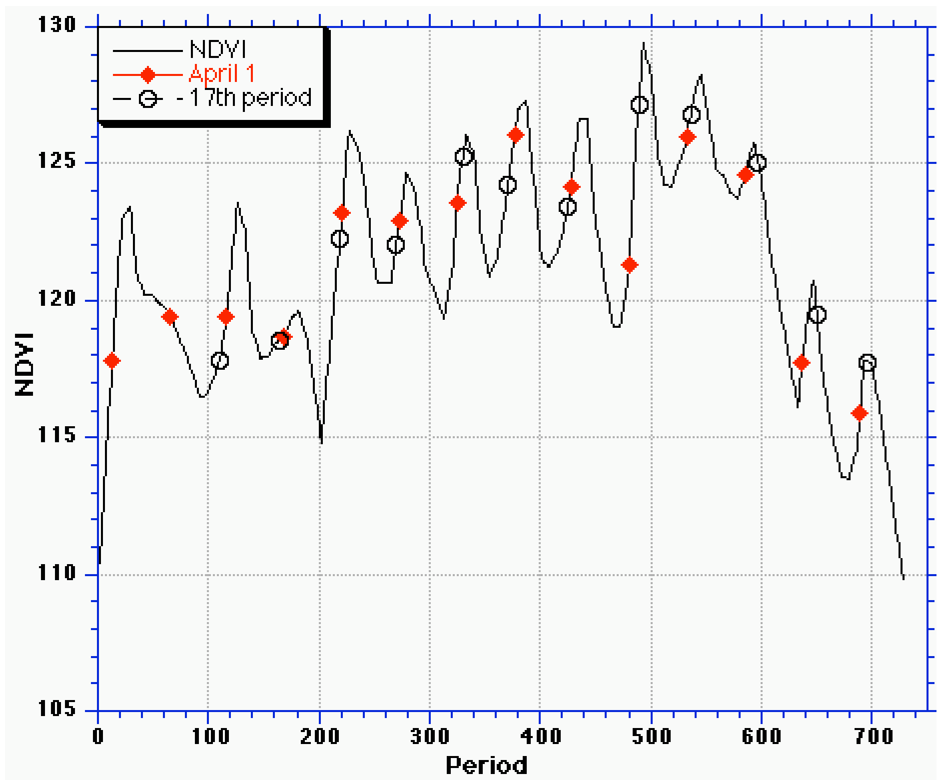


Figure 4-1. Smoothed time series for Fuel Model T pixel in Oregon showing annual variability of NDVI through the period-of-record (1989-2002). April 1st and the 17th week or period after the minimum are located as examples of calendar thresholds for green-up.

In many ways, the philosophy and approach of White et al. (1997) seems to fit the context of this application of NDVI to NFDRS. They characterized phenology as the study of recurring and highly variable vegetation cycles and the connection of these cycles to climate. Their goal was to develop a simple model capable of representing climatically induced phenological variability at a regional level. They encountered the same obstacle with phenology: most studies have been species specific. Their ecosystem approach and the NFDRS approach of this thesis need a wider phenology perspective.

White et al. (1997) argued that objectively defining an absolute beginning and ending of a growing season using satellite observations is practically impossible. Satellites cannot distinguish first leaf, budburst, or other precise phenology stages. However, this sort of precision is entirely unnecessary for fire danger rating. The definition of green-up for NFDRS (Schlobohm and Brain 2002) states, “Green-up should not be started when the first flush of green occurs in the area.” What White et al. (1997) suggest to be a limitation for some applications of satellite imagery is an appropriate feature for NFDRS. White et al. also believed that using the occurrence of most rapid growth to signal green-up rather than a single phenology stage such as budburst was most relevant for ecological models. This view also squares with the NFDRS concept of green-up, one where “the majority of vegetation is flush with growth.” NFDRS, with its large rating areas and relative index outputs, is analogous to an ecological model temporally and spatially.

The technique developed by White et al. in 1997 was called the $NDVI_{ratio}$:

$$NDVI_{ratio} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}, \qquad (5)$$

where $NDVI_{min}$ is the annual minimum NDVI value, $NDVI_{max}$ is the annual maximum NDVI value, and NDVI is the NDVI value for the time of interest. Essentially, $NDVI_{ratio}$ is a user-selected fraction of maximum NDVI or greenness for the year. Green-up based on $NDVI_{0.25}$ would occur at 25% of maximum NDVI (see figure 4-2). In this way, White proposed a method of standardizing NDVI so that it could be applied at an ecosystem scale. They concluded that $NDVI_{0.5}$ defined the period of most rapid growth in grasslands and deciduous broadleaf forests of the US. Subsequently, White et al. (1999, 2002) refined the $NDVI_{0.5}$ concept, and called it the seasonal midpoint NDVI (SMN).

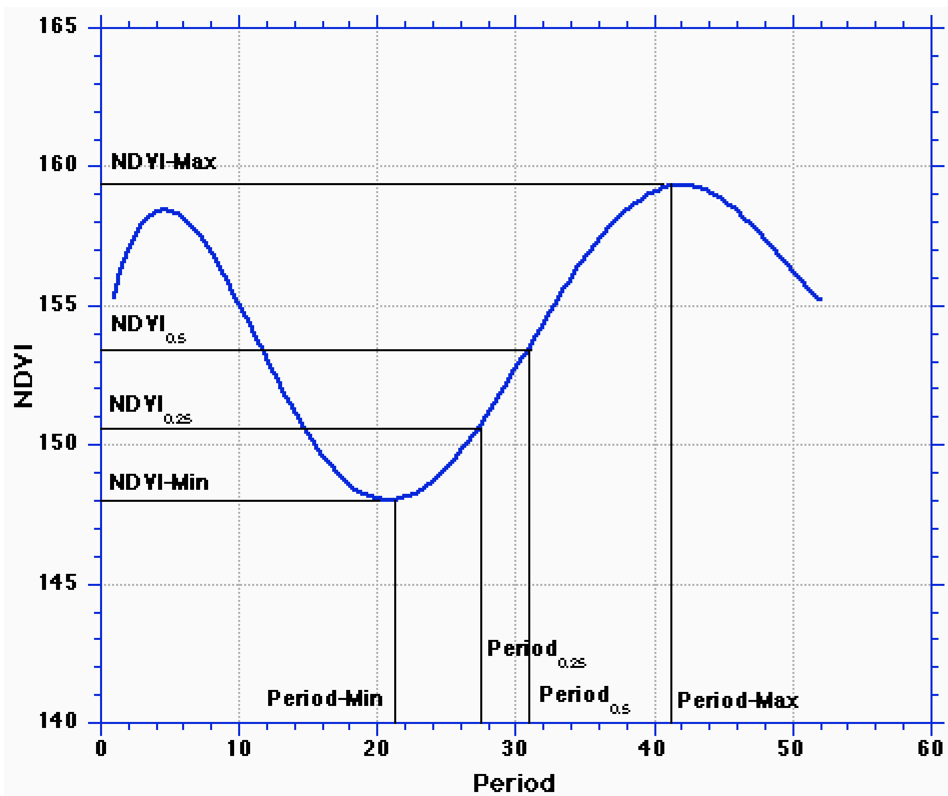


Figure 4-2. Example of a smoothed NDVI trend demonstrating the timing of maximum, minimum, $NDVI_{0.5}$ and $NDVI_{0.25}$ NDVI values.

## 4.2 Smoothers

A sample time series of 104 periods is shown in Figure 4-3 (from the central pixel at the California study area). NDVI observations may vary widely from period to period, due to partial cloud cover and other atmospheric interference during the period. Frequently, observations of vegetation are obscured by clouds or snow, and, therefore, are missing. To assess the possibility of a green-up event from week to week, a smoother must be applied to reveal the tendencies in the data. Smoothers should present the low frequency signal in the data and ignore the high frequency noise such as sudden spikes in the sequence (Velleman 1988). For purposes of this method, the smoother must meet the following requirements:

1) The smoother had to be able to process missing values and compute estimates for them. Missing values are a reality of the data set and NDVI imagery in general. However, an estimate is necessary for each period in order to maintain a 1-week temporal scale for green-up date declaration.
2) The smoother had to provide reasonable treatment at the series endpoints. Assessment of green-up status will occur on the leading edge (in time) of the time series rather than in the middle. The smoother needed to be able to provide estimates that remain central to the trend in the data at the boundary, but with limited influence from outliers and gaps of missing values.
3) FORTRAN code for the smoother had to be readily available for use. While the techniques involved in this method are not exclusive to

FORTRAN, the time availability of and the computer support knowledge base for this project required the use of pre-existing developed FORTRAN software.

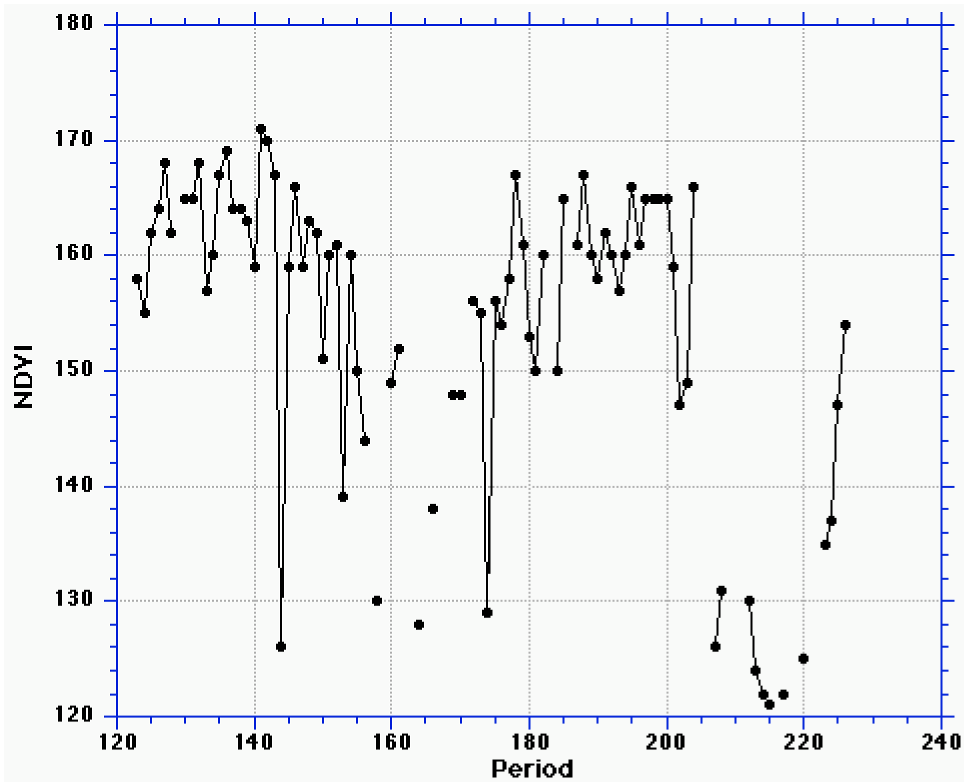


Figure 4-3. Plot of sample 104 periods demonstrating period-to-period variability

The polynomial smoother was the only one of several smoothers investigated that met all of the above requirements. For example, the Loess, or locally weighted regression scatter plot smoother (Cleveland 1979), may be technically more appropriate for requirements 1) and 2), but it was not readily available for bulk implementation. Future work with this study's proposed method should further explore computing options for alternative smoothers.

A polynomial curve fit is a non-linear regression model that takes the form:

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \ldots. + \beta_k x_i^k + \varepsilon \qquad i = 1,2,\ldots., n \qquad (6)$$

where $y_i$ is the dependent variable, $x_i$ is the independent variable, $\beta_0$, $\beta_1$, $\beta_2$,…, $\beta_k$ are the regression coefficients, and $\varepsilon$s are normal errors with mean zero and variance $\sigma^2$ (Visual Numerics 2003).

The user-defined degree of the polynomial determines the extent to which the polynomial describes peaks and troughs in the data sequence. Increasing curvature of the smoother comes with increasing degree of the polynomial equation.

One of the disadvantages of polynomials is boundary bias, due to the asymmetric contribution of observations to the smoother near the edge of the data sequence (Simonoff 1996). However, it can still provide reasonable NDVI estimates to demonstrate and test this method.

Smoother success at the leading edge (as time increases) of a sequence is critical because this is where assessments of green-up conditions will need to be made operationally (from week to week). Initially, the polynomial smoother was applied to a 52-period sequence. These proved to have unacceptable exaggeration or bias associated with missing values as shown in figure 4-4. The use of a 104-period sequence and 5$^{th}$ degree polynomial function seemed to mitigate the influence of missing values. However, the fact that missing values in this data set can be on the leading edge of the polynomial led to establishing a rule that green-up dates will not be declared for missing values on the leading edge.

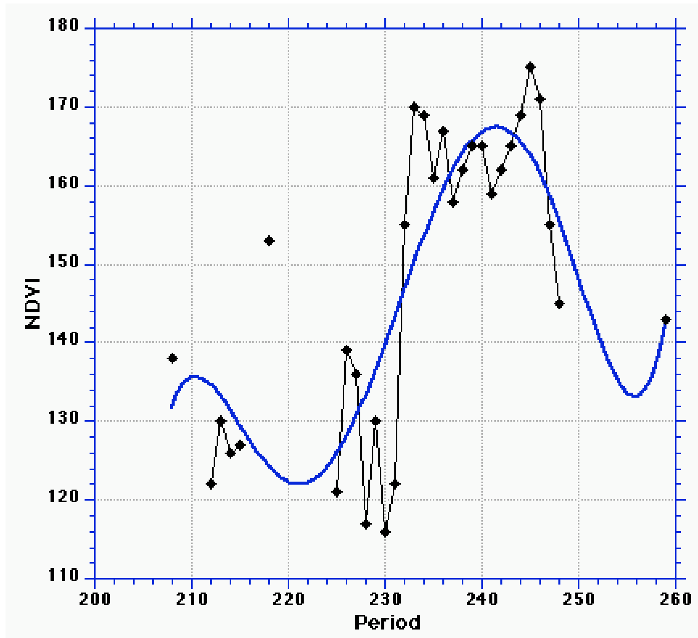


Figure 4-4. Example of smoother exaggeration in a 52-period NDVI time series

## 4.3 The Integral Method: Applying the $NDVI_{ratio}$ Operationally

Previous NDVI-vegetative growth studies had the advantage of examining only historical information and discussing its relationships and implications. The objective here is to define a process that identifies the live fuel conditions of green-up as they happen operationally.

White et al. (1997) used the maximum and minimum NDVI values for a single year to determine onset of greenness for that year. Operationally, the annual maximum is not yet known and green-up must be declared before the NDVI maximum occurs each year. The comparison of the current growing season trend of NDVI to the climatology for NDVI-derived green-up is here proposed by computing the integral of the smoothed NDVI values. While there are similarities to White's seasonal midpoint NDVI (SMN), this approach is more directly based on White's (1997) $NDVI_{ratio}$ of 0.5. By employing the area under the curve as a threshold for green-up, this approach is independent of the inter-annual variability in the magnitude of NDVI described in Figure 4-1.

The first step is to compute the climatological NDVI values for each of the 52 annual periods (weeks) of the year as described in Chapter 3. Next, the smoother is fit to the climatological NDVI values as shown in figures 4-5, 4-6, and 4-7 for the central pixel in each study area. Then the area under the curve bounded by the period of the minimum ($Period_{min}$) and the period when $NDVI_{0.5}$ is achieved ($Period_{0.5}$) on the abscissa and by the $NDVI_{min}$ and $NDVI_{0.5}$ on the ordinate (see figures 4-8, 4-9, and 4-10) is computed. This becomes the target area for achieving green-up in each individual year. $Period_{0.5}$ will be referred to as the climatological $NDVI_{0.5}$ green-up date.

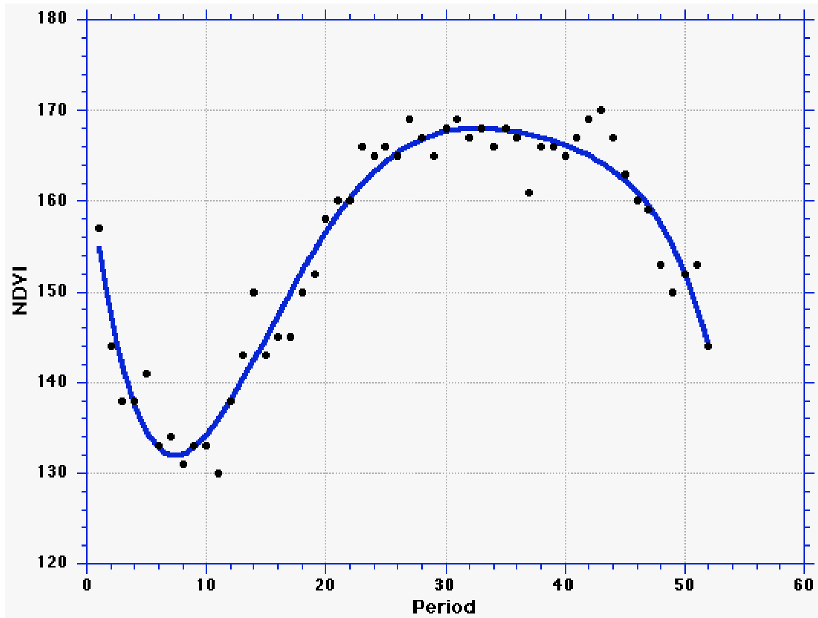


Figure 4-5. Fit of the polynomial smoother to the 1-52 week (period) climatology for NDVI at the central pixel of the California study area.

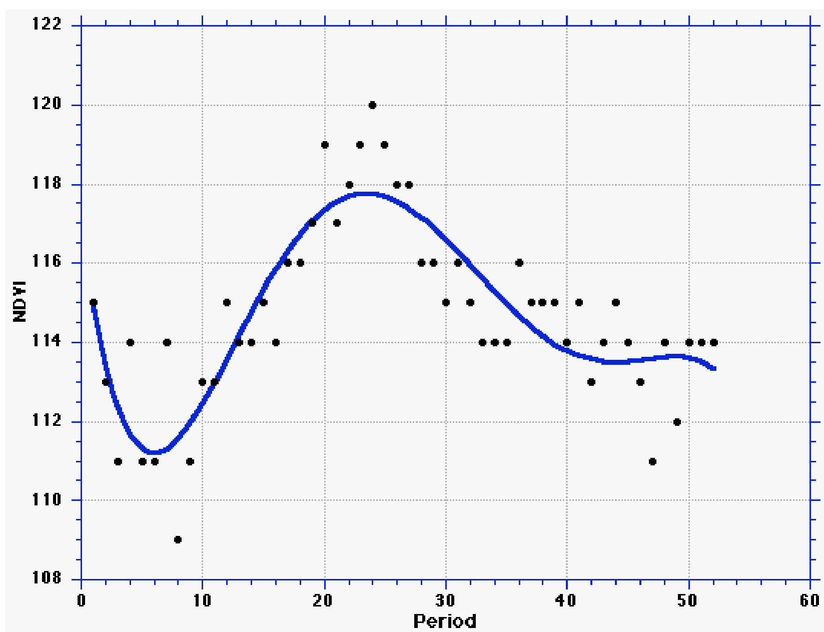


Figure 4-6. Fit of the polynomial smoother to the 1-52 week (period) climatology for NDVI at the central pixel of the Nevada study area.

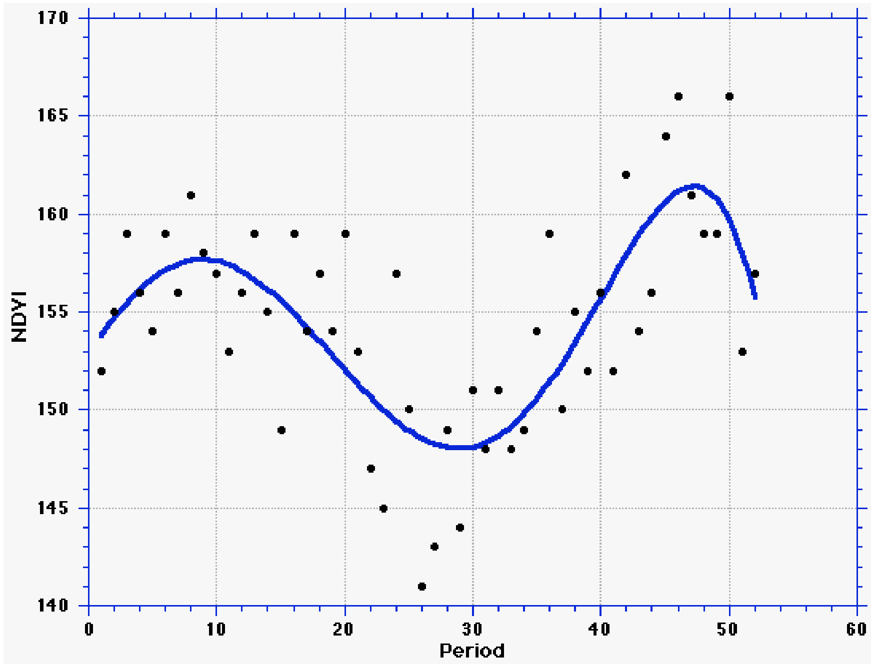


Figure 4-7. Fit of the polynomial smoother to the 1-52 week (period) climatology for NDVI at the central pixel of the Florida study area.

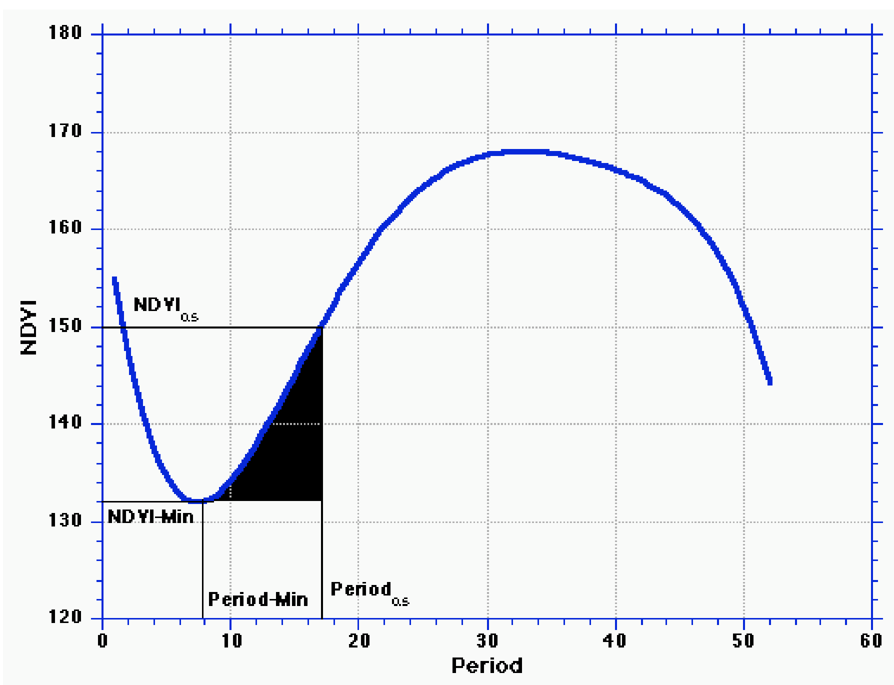


Figure 4-8. The target area (shaded) for the central pixel of the California study area, bounded by the period of the minimum ($Period_{min}$) and the period when $NDVI_{0.5}$ is achieved ($Period_{0.5}$) on the abscissa and by the $NDVI_{min}$ and $NDVI_{0.5}$ on the ordinate.

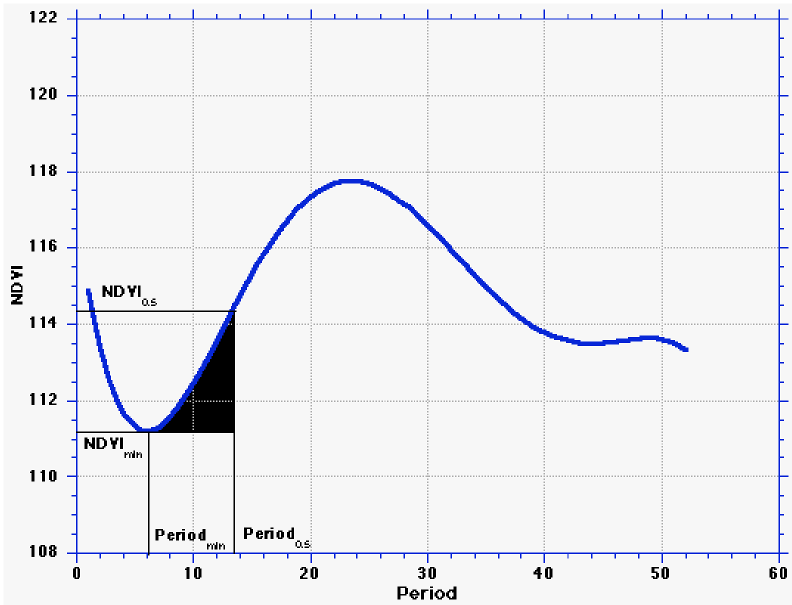


Figure 4-9. The target area (shaded) for the central pixel of the Nevada study area, bounded by the period of the minimum ($Period_{min}$) and the period when $NDVI_{0.5}$ is achieved ($Period_{0.5}$) on the abscissa and by the $NDVI_{min}$ and $NDVI_{0.5}$ on the ordinate.

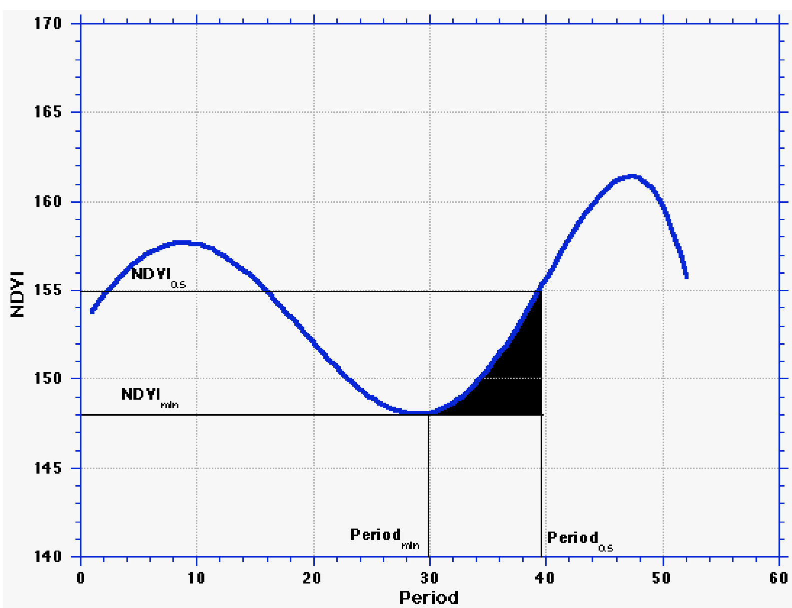


Figure 4-10. The target area (shaded) for the central pixel of the Florida study area, bounded by the period of the minimum ($Period_{min}$) and the period when $NDVI_{0.5}$ is achieved ($Period_{0.5}$) on the abscissa and by the $NDVI_{min}$ and $NDVI_{0.5}$ on the ordinate.

To determine green-up dates for each year in the period of record, the next step is to compute the integral after each minimum in the smoothed data set. This is done on the leading edge of the 104-period sequence as if it were a real time calculation as shown in figure 4-11. The 104-period sequence is moved forward one period at a time until the target area is achieved. At each step forward, the polynomial smoother is fit to the data. The slope of the smoother from periods 103 to 104 is computed. If the slope is negative, as in the upper left plot of figure 4-11, the smoother is assumed to be declining from a maximum. This condition is necessary before an integral is computed. At the first step forward with a positive slope from periods 103 to 104, the smoother is assumed to be rising, and the most recent minimum prior to period 104 is determined. The integral from the minimum to period 104 is computed and compared to the target area. If the integral is less than the target area, as in the upper right plot of figure 4-11, the process continues. At the first step forward to equal or exceed the target area, the period-of-record period number (1-728) corresponding to analysis period 104 is declared the green-up date. For example, if the target area were achieved at period 645, as in the lower plot in figure 4-11, this is translated to the calendar period (1-52) of 21 and the calendar date based on the EDC/FS data set of May 24, 2001. This process begins at the beginning of the record and continues until green-up dates are identified for as much of the dataset as possible.

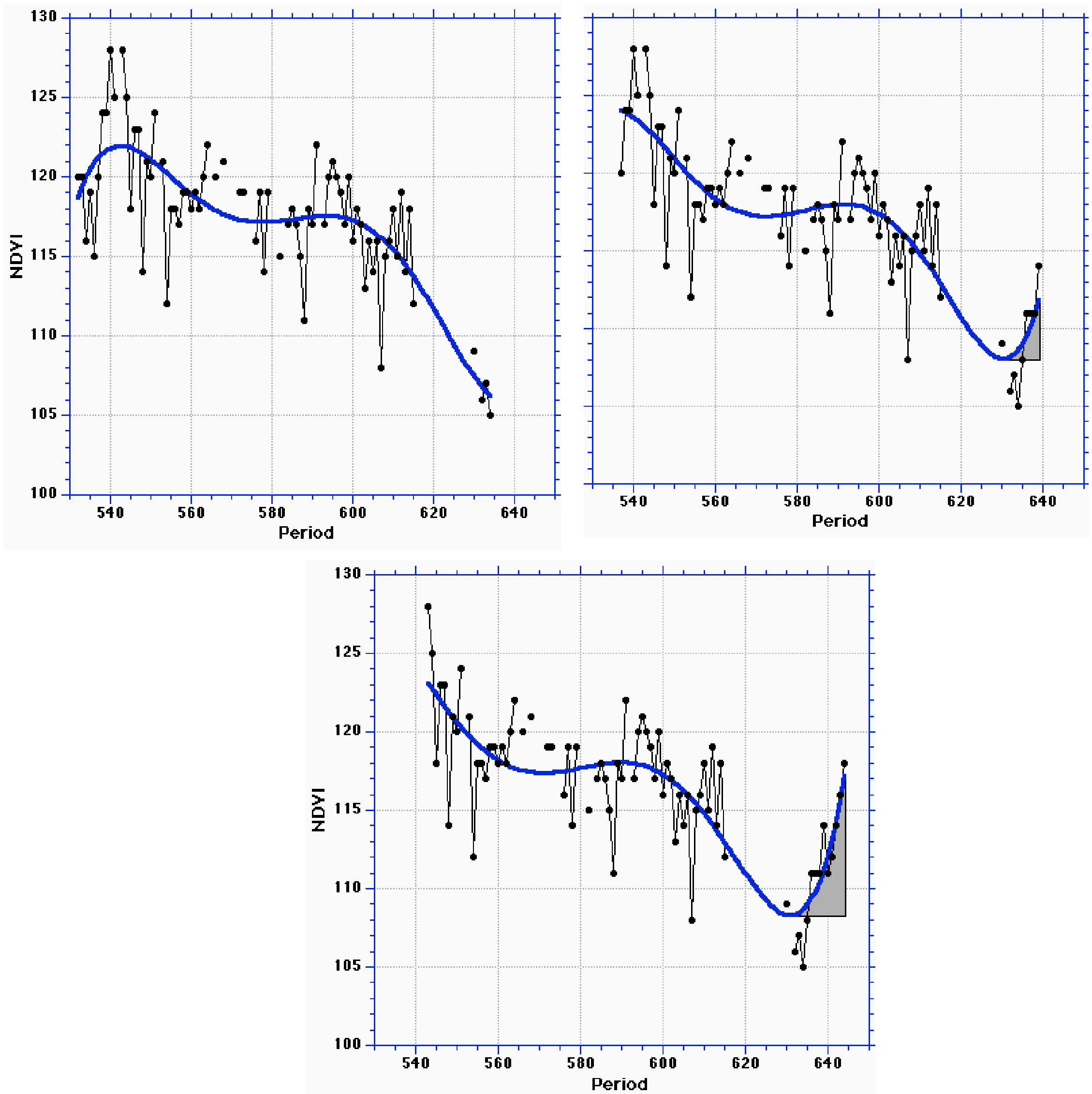


Figure 4-11. Example of 104-period smoothed NDVI and computation of the integral under the curve at the leading edge. Green-up is declared when this integral reaches the target area.

## 4.4 Programming

Processing of this methodology required a sequence of seven programs written in the FORTRAN 77 language. Each program performed a unique function in the process and each was modified to make calculations for each pixel category (fuel model, cover type, difference bin) and study area. Computer programs and functions are summarized is Appendix E.

# Chapter 5 Analysis

The analysis of the proposed method of employing the integral of the smoothed NDVI to identify green-up will closely follow the sequence of steps in the study. Each discovery generally influenced successive techniques and insights into the data, and the method.

## 5.1 Fuel Model Sites

Ideally, pixels of a common classification, such as NFDRS fuel model T, will have similar NDVI signals whose processing for a green-up determination can be performed en masse with one target area. This would greatly enhance computing of national scale maps. To test this possibility, two test sites in Oregon were examined (see figure 3-7).

The analysis of fuel model G (over-mature short-needled conifer) and T (sagebrush with grass understory) sites demonstrated that the NDVI signal was distinctly different for these two areas that represent two distinctly different fuel models. Box plots of the NDVI signal for 1990 for 4 adjacent 2x2 pixels are shown in figure 5-1. While not unexpected, this result was necessary in order to verify that the EDC/FS NDVI data set could differentiate between differently vegetated locations.

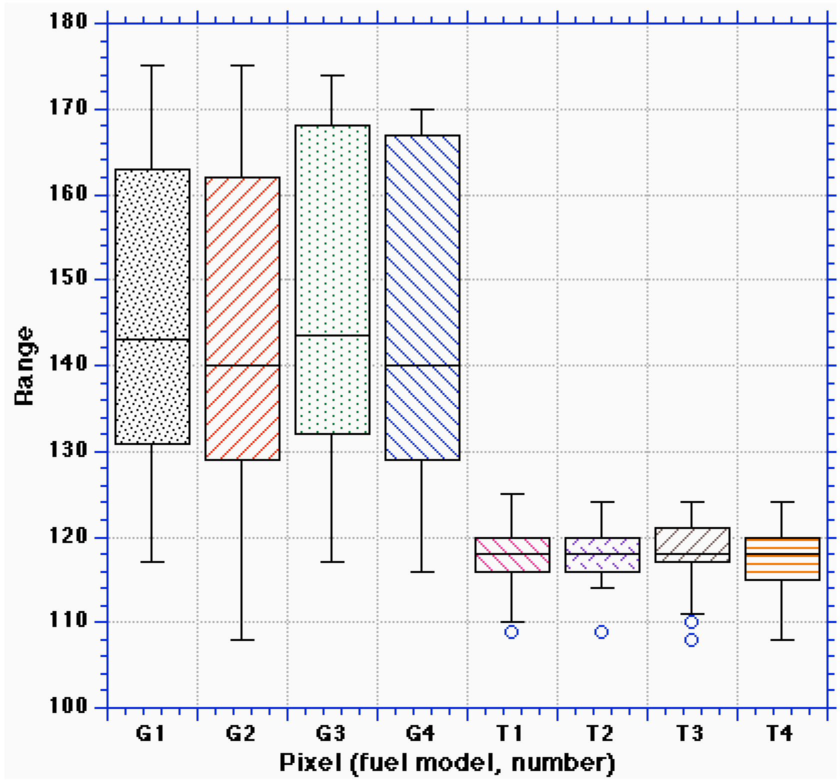


Figure 5-1. Distribution of the 1990 NDVI signal for 4 pixels at the study sites for fuel models G and T.

Could the target areas for the two fuel model sites be applied to other locations for the same fuel model or would each pixel need to have its own target area in order to apply the proposed integral method? Two hundred random pixels were analyzed in both fuel models from throughout the US. Pixels were selected using the FORTRAN 77 algorithm AS183, a random number generator (Wichmann and Hill 1982). Green-up dates were computed using the integral method and compared to the climatological $NDVI_{0.5}$ green-up date (the period of $NDVI_{0.5}$ for the pixel's NDVI climatology). The distribution of the difference between the integral method green-up dates and the climatological $NDVI_{0.5}$ green-up date is shown in figures 5-2 and 5-3. These results address the question: what is the variation in the integral method green-up dates as compared to climatology for each pixel and fuel model? The difference for the 200 G pixels fell generally between 2 weeks early and 2 weeks late. A two-week difference in green-up between climatology and what would be computed in bulk for all fuel model G pixels is fairly remarkable and suggests a uniformity of NDVI signal for these pixels. Considering the minimal influence of green-up on the typical NFDRS output for fuel model G, the energy release component, this amount of variability is likely to be acceptable to field managers.

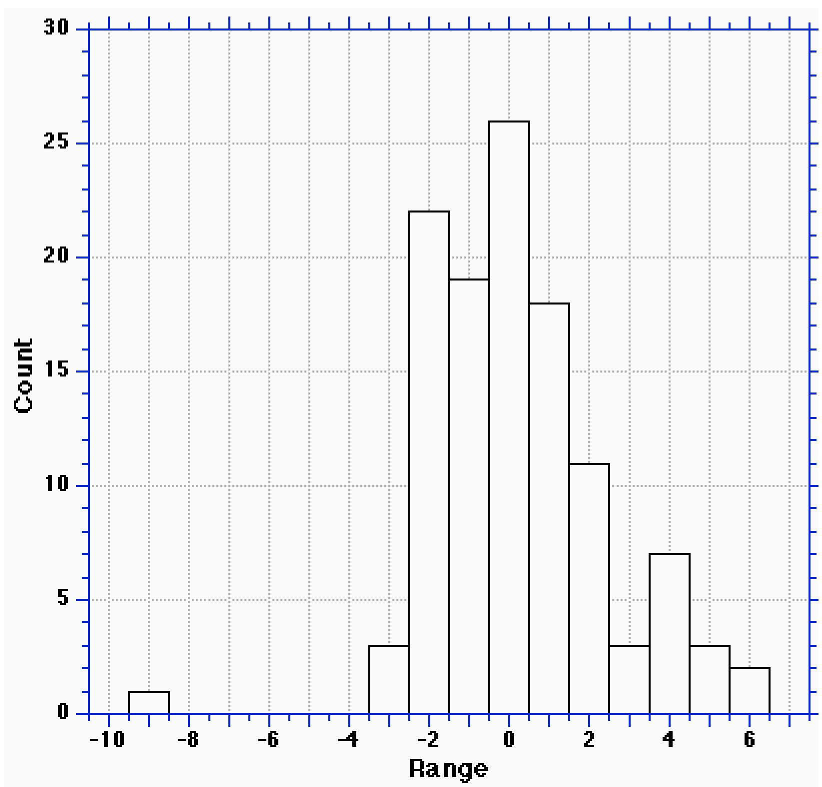


Figure 5-2. Distribution of the difference between integral method green-up dates and the climatological $NDVI_{0.5}$ green-up date for fuel model G pixels.

The difference for the 200 T pixels fell generally between 4 weeks early and 4 weeks late (figure 5-3). In a fuel model like T for which green-up can significantly influence fire danger ratings, 4 weeks represents too much variability for operational usefulness. Thus a fuel model-wide target area does not seem to be appropriate for fuel model T.

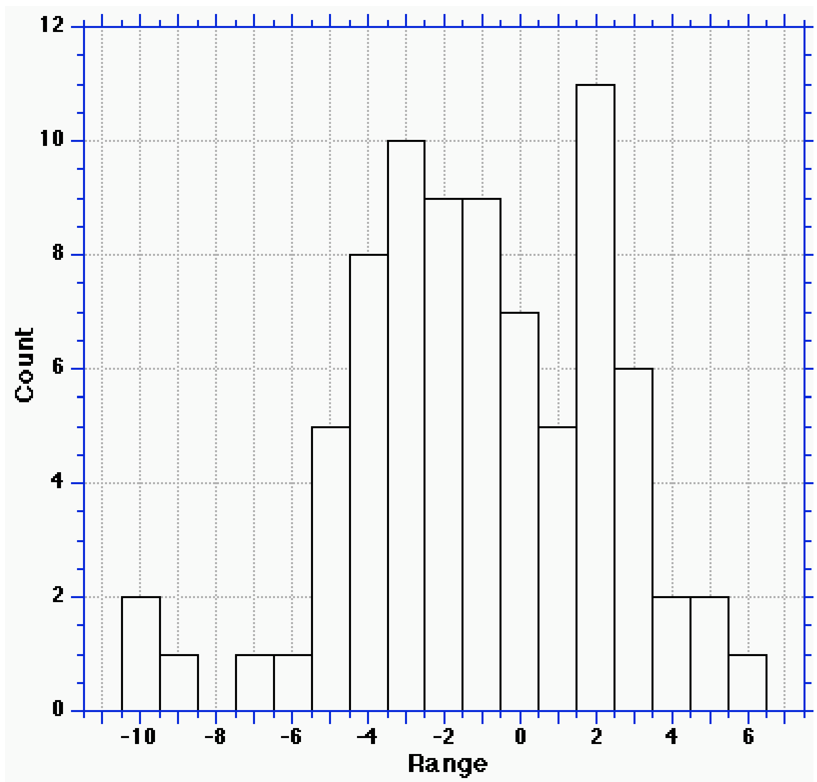


Figure 5-3. Distribution of the difference between integral method green-up dates and the climatological $NDVI_{0.5}$ green-up date for fuel model T pixels.

Analysis of current cover types revealed that pixels classified as fuel model T are classified as 20 different cover types, ranging from water to desert shrub to redwood forest. Pixels classified as fuel model G also consist of many cover types, but they are predominantly western forest cover types for which fuel model G would be applied for fire danger rating. This inherent variability in the fuel model data set led to consideration that cover types might be utilized to generalize green-up parameters. Details of the cover type classifications for both fuel model G and T pixels throughout the US can be found in Appendix F.

### 5.2 Current Cover Types

The two most common cover types within the fuel model T classification are desert shrub (25 percent of all T pixels) and other shrub (55 percent of all T pixels). These two pixel categories (desert and other shrub) were also sampled for 200 random pixels. The integrals of NDVI climatology were computed for each pixel and their distribution compared to that of the fuel model T pixels is shown in figure 5-4. This distribution suggests that the vegetation in desert shrub pixels exhibit the NDVI signal of vegetation in fuel model T pixels more closely than those in the other shrub pixels even though the other shrub cover type represents a majority of T pixels.

Four examples of 52-period climatologies for desert shrub-classified pixels demonstrate the variability of the amplitude of NDVI signals in this cover type (figure 5-5). These pixels are located near Laredo, Texas; Dugway, Utah; Needles, California; and Holbrook, Arizona.

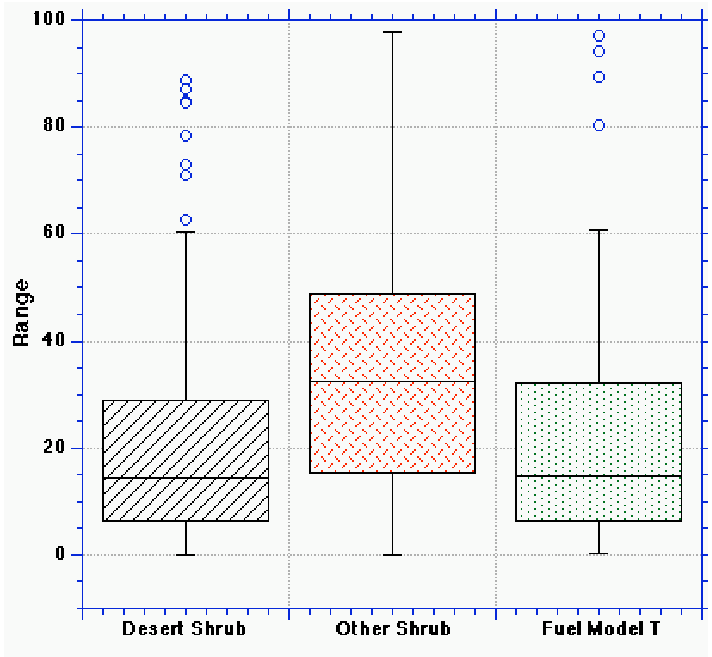


Figure 5-4. Distribution of climatological integral computed at $NDVI_{0.5}$ (the target area) for desert shrub and other shrub cover types and fuel model T.

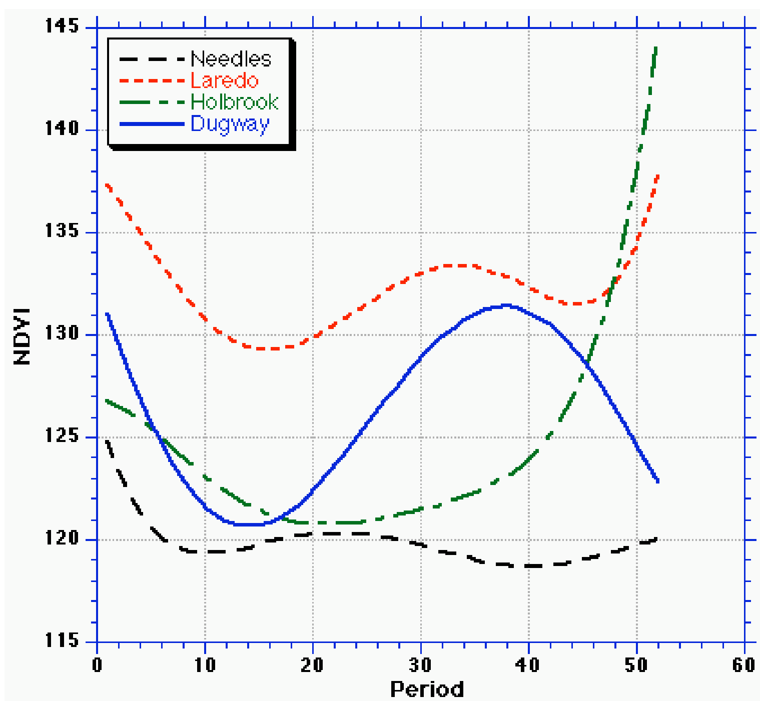


Figure 5-5. Four 52-period climatologies of NDVI in desert shrub cover type pixels.

Green-up dates for desert shrub pixels were computed based on the integral method and compared to the climatological green-up period (figure 5-6). As with the pixels in fuel model T, a spread of at least 4 weeks on either side of climatology describes the NDVI signal variability in desert shrub cover type pixels. This variability, which is further explained in section 5.3, led to the conclusion that cover types were also not satisfactory pixel classifications for the integral method.

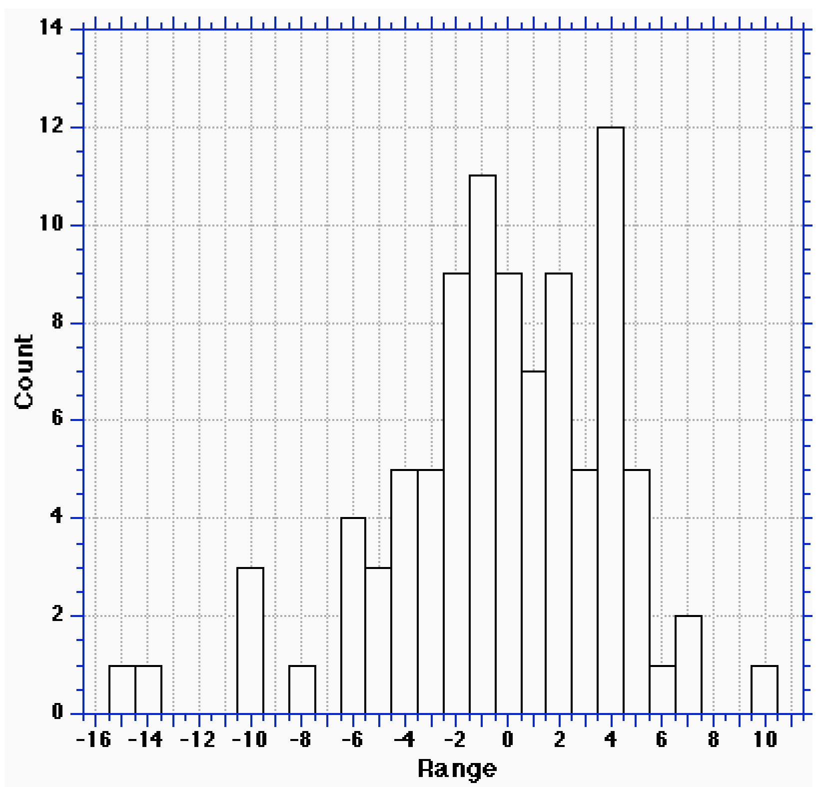


Figure 5-6. Distribution of the difference between integral method green-up dates and the climatological $NDVI_{0.5}$ green-up date for desert shrub cover type pixels.

## 5.3 Difference Bins

Given the apparent NDVI signal variability of fuel model and cover type pixels with respect to this method, a new approach to classifying pixels was developed, as described in section 3.2.3. The idea is that pixels are classified in relation to the amplitude of their climatological NDVI signal. Rather than use classifications created for other purposes, this approach classifies pixels solely on their NDVI signature, upon which the climatological target area depends. Thus, considering pixels in terms of difference bins may be important for the proposed method to meet the stated objectives.

Cover type and fuel model classifications were found to place pixels of one classification, such as fuel model T, across a wide range of difference bins, which could explain the variability of both fuel models and cover types for this application. The percentages of difference bins found in 6 cover types are shown in figure 5-7, 5-8, and 5-9. Consider the plot for desert shrub cover type. Most pixels in this target group fall into difference bins 6-10 as might be expected. The NDVI signal for these pixels is relatively flat. A target area based on these flat signals could be developed, but it would not be sufficient for 13 percent of the pixels in this cover type that are in difference bin 16 or higher. Grassland and pinyon/juniper cover types are two examples of cover types with even wider ranges of NDVI signal.

Annual climatologies for sample pixels from difference bins 2, 22, and 90 demonstrate that difference bins have pixels with distinct NDVI signals and these signals display consistent amplitude and wavelength (figure 5-10). Difference bins 2 and 90 are shown here to demonstrate the extremes of this classification. In reality, there are few pixels classified in these bins.

### 5.4 Study Areas

To assess the success and applicability of computing green-up for pixels organized by difference bins, three study areas were selected as described in Chapter 3.

NDVI seasonal trends for pixels classified by difference bin were analyzed with the integral method to determine green-up for each year in the period of record. Green-up date statistics and dates are summarized for each pixel in each study area in tables 5-1 (California), 5-2 (Nevada), and 5-3 (Florida). The median is determined as the measure of central tendency due to the small number of years in the data set. The pseudosigma, rounded to the nearest week, is appropriate in this case as the measure of variation about the median, and is computed as:

$$Pseudosigma = \frac{IQR}{1.349}, \qquad (7)$$

where IQR is the inter-quartile range (Hoaglin et al. 1983).

Each calendar period (1-52) generally corresponds to a unique calendar date in each year of the EDC/FS data set (i.e. period 20 ends May 23 in 1989, May 19 in 1994; see Appendix D). To simplify this discussion, however, each calendar period is translated to the corresponding calendar date for 1 year

(2001). The actual correspondence of period and date will be important to operational applications, but that level of precision is not necessary here.

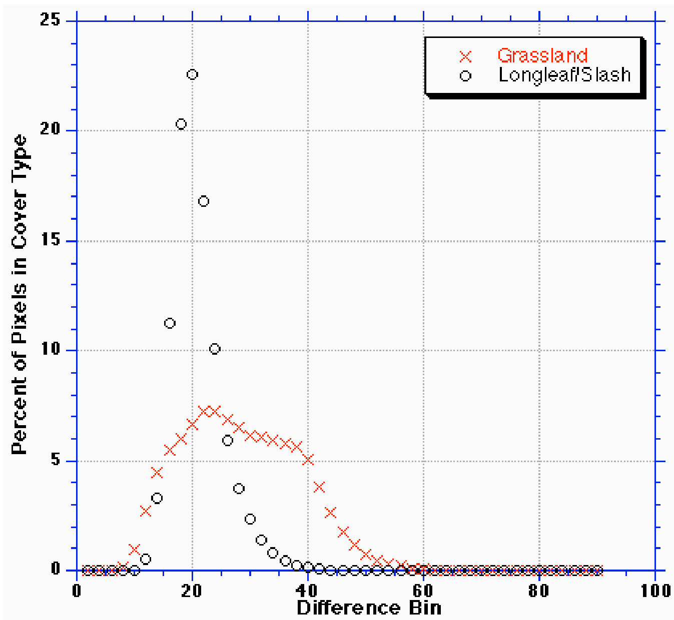


Figure 5-7. Percent of pixels classified as grassland and longleaf/slash pine cover types for each difference bin.

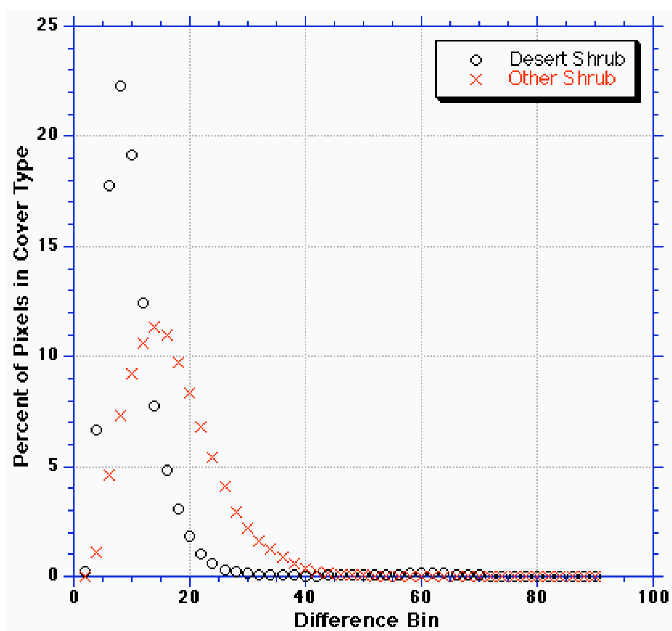


Figure 5-8. Percent of pixels classified as desert shrub and other shrub cover types for each difference bin.

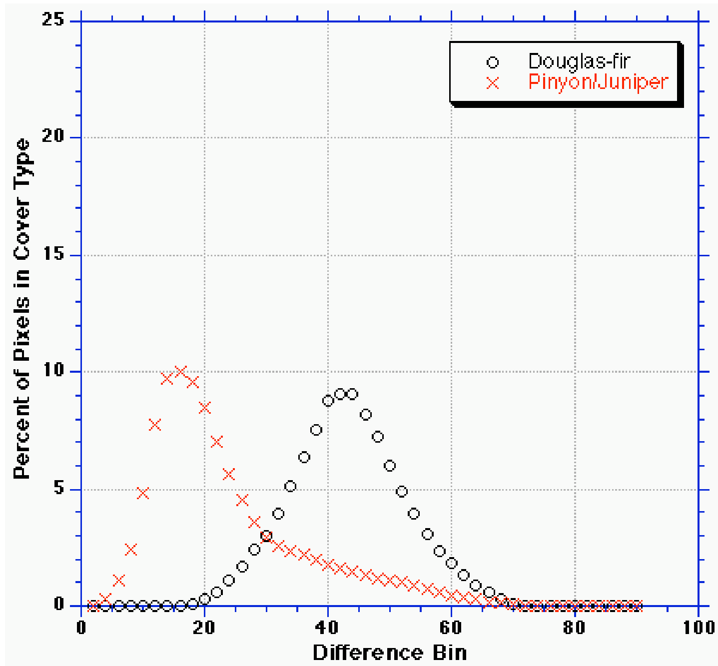


Figure 5-9. Percent of pixels classified as Douglas-fir and pinyon-juniper cover types for each difference bin.

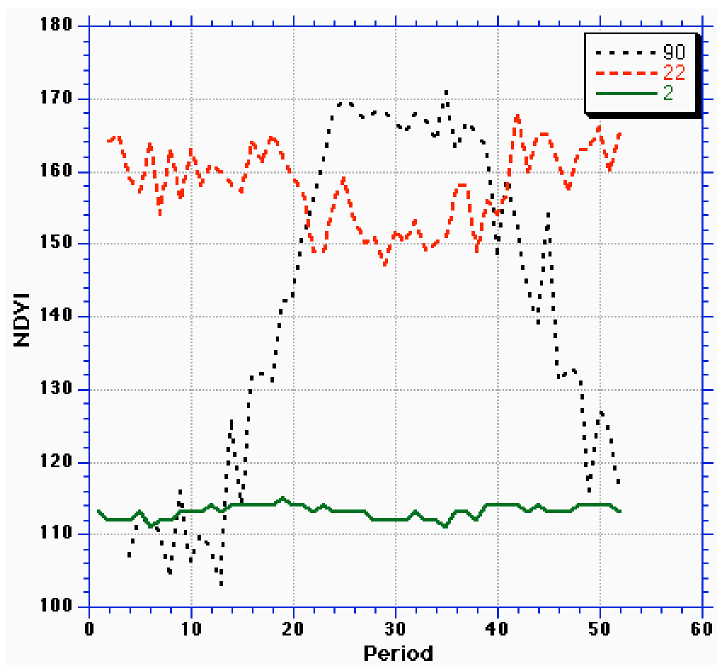


Figure 5-10. The 52-period NDVI climatology for three pixels, one each from difference bins 2, 22, and 90.

| Median (period number, start date) | | | Pseudosigma (periods) | | |
|---|---|---|---|---|---|
| 23 (Jun 7) | 21 (May 24) | 23 (Jun 7) | 3 | 1 | 2 |
| 23 (Jun 7) | 23 (Jun 7) | 22 (May 31) | 2 | 3 | 3 |
| 23 (Jun 7) | 22 (May 31) | 22 (May 31) | 2 | 2 | 2 |
| **Minimum (period number, start date)** | | | **Maximum (period number, start date)** | | |
| 20 (May 17) | 19 (May 10) | 19 (May 10) | 27 (Jul 5) | 25 (Jun 21) | 25 (Jun 21) |
| 19 (May 10) | 19 (May 10) | 19 (May 10) | 25 (Jun 21) | 25 (Jun 21) | 25 (Jun 21) |
| 17 (Apr 27) | 17 (Apr 27) | 19 (May 10) | 27 (Jul 5) | 25 (Jun 21) | 27 (Jul 5) |

Table 5-1. Green-up date statistics (median, pseudosigma, and range) for 9 pixels in the California study area using the integral method.

| Median (period number, start date) | | | Pseudosigma (periods) | | |
|---|---|---|---|---|---|
| 14 (Apr 5) | 14 (Apr 5) | | 3 | 2 | |
| 16 (Apr 19) | 14 (Apr 5) | 14 (Apr 5) | 5 | 4 | 2 |
| 16 (Apr 19) | 14 (Apr 5) | 14 (Apr 5) | 3 | 4 | 4 |
| **Minimum (period number, start date)** | | | **Maximum (period number, start date)** | | |
| 11 (Mar 15) | 9 (Mar 1) | | 20 (May 17) | 17 (Apr 26) | |
| 9 (Mar 2) | 10 (Mar 8) | 10 (Mar 8) | 24 (Jun 14) | 23 (Jun 7) | 17 (Apr 26) |
| 11 (Mar 15) | 9 (Mar 1) | 9 (Mar 1) | 21 (May 24) | 21 (May 24) | 24 (Jun 14) |

Table 5-2. Green-up date statistics (median, pseudosigma, and range) for 8 pixels in the Nevada study area using the integral method.

| Median (period number, start date) | | | Pseudosigma (weeks) | | |
|---|---|---|---|---|---|
| 38 (Sep 20) | 44 (Nov 1) | 41 (Oct 11) | 4 | 3 | 3 |
| 42 (Oct 18) | 41 (Oct 11) | 42 (Oct 18) | 3 | 3 | 3 |
| 42 (Oct 18) | 41 (Oct 11) | 40 (Oct 4) | 3 | 2 | 3 |
| **Minimum (period number, start date)** | | | **Maximum (period number, start date)** | | |
| 34 (Aug 23) | 39 (Sep 27) | 35 (Aug 30) | 52 (Dec 27) | 52 (Dec 27) | 50 (Dec 13) |
| 33 (Aug 16) | 35 (Aug 30) | 36 (Sep 6) | 52 (Dec 27) | 52 (Dec 27) | 52 (Dec 27) |
| 33 (Aug 16) | 38 (Sep 20) | 35 (Aug 30) | 52 (Dec 27) | 52 (Dec 27) | 52 (Dec 27) |

Table 5-3. Green-up date statistics (median, pseudosigma, and range) for 9 pixels in the Florida study area using the integral method.

5.4.1 California

At each pixel of the California site, the integral method identified one green-up date during the spring of each year between 1991-2002. This is the set of years that can be analyzed using 104 periods at each step. There were no years with multiple green-up dates, such as one in spring and fall. The median green-up date (late May – early June), spread (late April – early July), and variation (2-3 weeks around the median) are reasonable dates for this location based on the climate of the area. The median date is nearly centered on the spread from earliest to latest dates and the expected variation is consistent with the results from the mature conifer-fuel model G test site (figure 5-2) in Oregon. The consistency of the median and spread between neighboring pixels relative to the Nevada and Florida sites suggests a more consistent spring season. The variation between neighboring pixels is most likely due to influences of aspect, and slope upon vegetation condition.

Green-up dates used by local fire managers on nearby NFDRS weather stations in 2003 were May 15 at Bald Mountain station sited at 1400 meters elevation and June 3 at Hell Hole station sited at 1600 meters elevation. Traces are plotted in figure 5-9 for herbaceous fuel moisture (FmH) and energy release component (ERC) at Hell Hole station in 1996 using the median (June 7) and agency (June 3) green-up dates. Records of the 1996 green-up date for this station are not available, as explained in section 2-1. Use of the current (2003) or other green-up date, while not necessarily historically accurate, is the same procedure that is used by fire managers who conduct historical analysis with existing software packages. The increase in FmH associated with green-up is delayed and slightly suppressed with the June 7 date, but this is of minimal significance to reported fire danger. The ERC trace is the same either way, thus the integral method is capable of providing green-up dates that produce outputs identical to those of the current system.

The ERC trace in figure 5-11 declines from about 55 to 0 in less than two weeks during the middle of May. Any drop of this magnitude for the ERC is the result of precipitation duration significant enough to increase fuel moisture of large fuels. Such a precipitation event, coupled with its impact on vegetation moisture may be an appropriate time to declare green-up at this location. Indeed, the actual green-up estimates for 1996 by the integral method ranged from May 2 to May 16. This demonstrates that the integral method can identify green-up dates that match those suggested through the processing of NFDRS historical weather records.

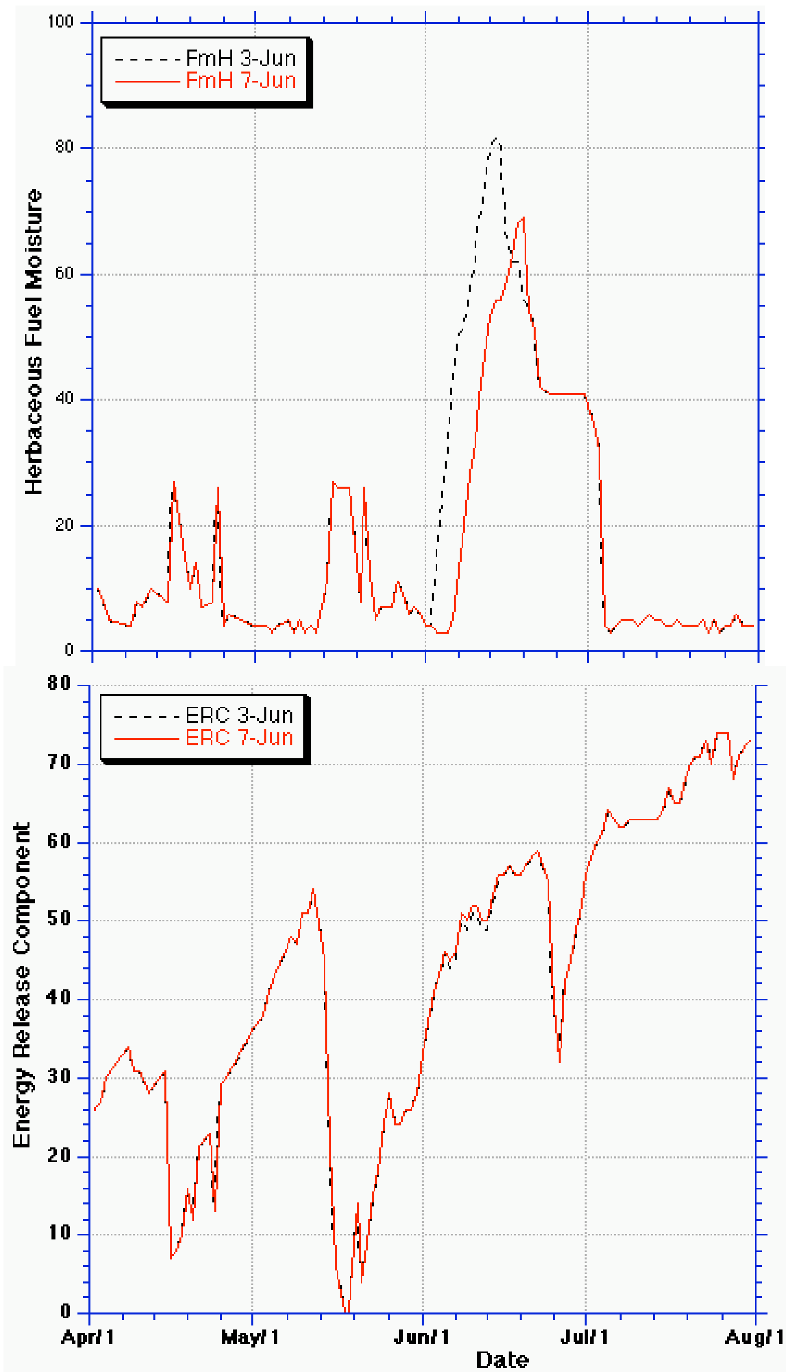


Figure 5-11. Comparison of traces for herbaceous fuel moisture and energy release component based on median integral method-derived green-up and agency green-up date entry for 1996 weather data from Hell Hole station.

5.4.2. Nevada

At the Nevada site, one spring green-up date per year was identified (1991-2002). There were no green-up dates declared at other times of the year. The median green-up date (late to mid April), spread (early March – mid June), and variation (2-5 weeks around the median) are reasonable dates for this location.

Pixel 3 (upper right) was not included because the climatological minimum occurred at period 52, the last week of the year, which resulted in no target area being determined. In the other 8 pixels, the minimum occurred in period 5-7, followed by 7-8 periods before the climatological green-up period. The reason the pixel 3 minimum occurred at period 52 is most likely because of the strict use of a 1-52 period analysis sequence, the proximity of the climatological minimum to the beginning or end of the sequence, and smoother end-point issues. This situation could be resolved by shifting the set of 52 periods used to develop climatology for this location to begin and end in the fall, for example at periods 43 and 42, respectively. This would place the late-winter – early-spring minimum NDVI signal in the middle, rather than the beginning or end, of the data sequence.

Green-up dates used by local fire managers on nearby NFDRS weather stations in 2003 were April 15 at Fish Springs station and May 16 at Desatoya station. Traces are plotted in figure 5-12 for FmH and burning index (BI) at Desatoya station in 2000 using the agency (May 16) green-up date and the date suggested by the integral method for 2000 (March 16). Declaring green-up as late as May 16 that year had no apparent impact on fire danger and would have kept the BI relatively high during April. Declaring green-up on March 16 produced a spike in FmH and a depression of the BI, as is generally expected when the green-up declaration approximates actual conditions. These results demonstrate that the integral method is capable of identifying appropriate green-up dates in this sparsely vegetated study area.

The median date is nearly centered on the spread from earliest to latest dates and the expected variation is longer than at the California site. This range of early to late green-up dates is most likely due to the interannual variability of springtime precipitation at this arid site. The variation in median and spread values between neighboring pixels suggests the influences of aspect, slope, and locally variable precipitation on vegetation condition. This level of precision for green-up is not possible with today's ocular estimate of a rating area.

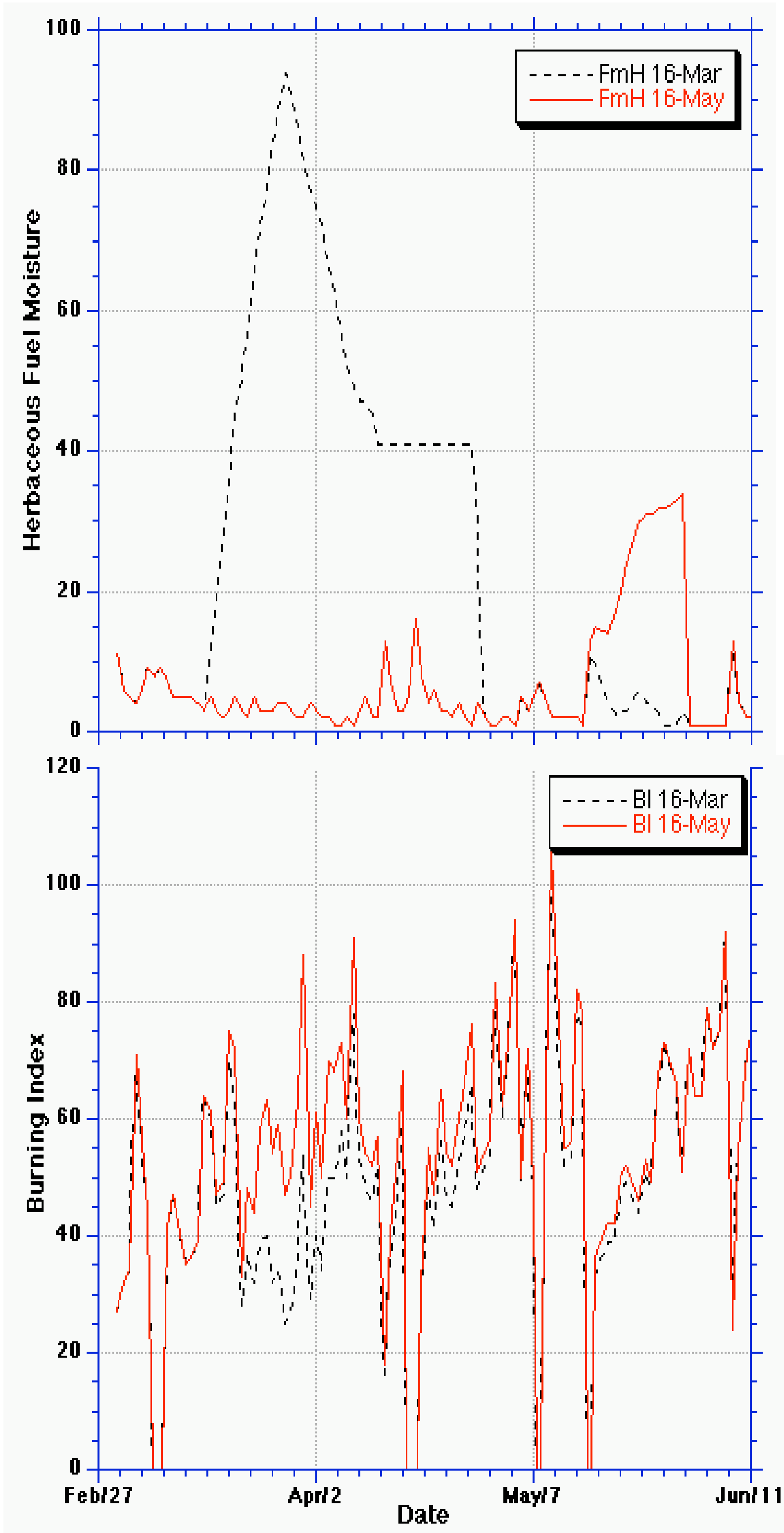


Figure 5-12. Comparison of traces for herbaceous fuel moisture and burning index based on integral method-derived 2000 green-up date and available (2003) agency green-up date applied to 2000 weather data from Desatoya station.

### 5.4.3. Florida

At the Florida site, the integral method identified at least one green-up date in every year. Fall green-up occurred in each year having fall data (1990-2001) and a spring green-up was identified for some pixels during 1991-1996 and 2001. For this analysis, green-up dates from August to December were considered fall green-up dates; spring dates occurred from January to June. The median fall green-up date (late September – early November), spread (mid-August – late December), and variation (3 weeks around the median) are reasonable dates for this location based on the climate of the area. Green-up dates or season codes used by local fire managers on nearby NFDRS weather stations were not available from WIMS for comparison.

The annual climatology for the Florida pixels shows that the fall increase in NDVI is of greater amplitude than in the spring. The climatology for pixel 3 (upper right in the 3X3 grid) is shown in figure 5-13 as an example. Since all increases in NDVI were compared to the target area developed from fall data, it is clear why only one green-up was declared for some years in Florida: the target area was too large for some of the spring NDVI signals. If a second target area was identified so that both spring and fall green-ups were assessed separately using their own climatology, then it is possible that this method could identify two green-up periods each year.

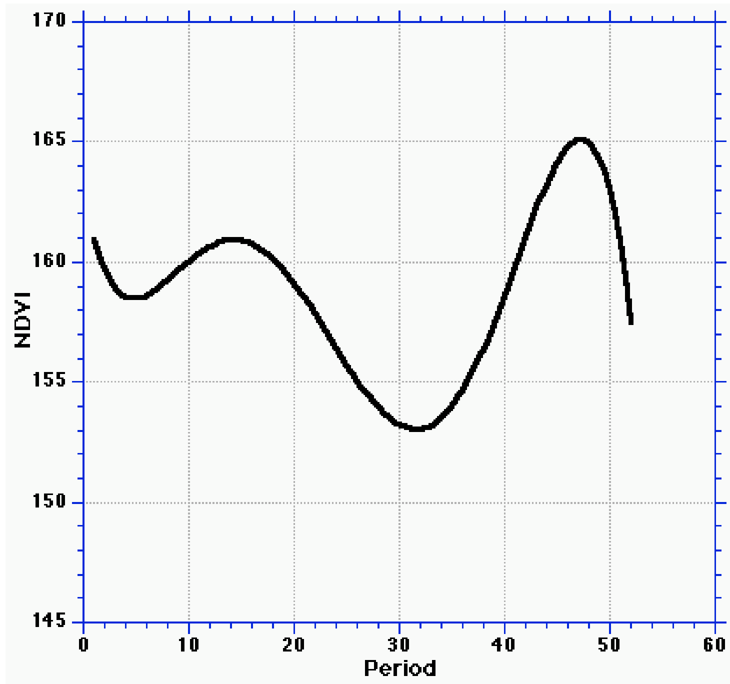


Figure 5-13. Annual period climatology for pixel 3 in Florida showing the difference in spring and fall increases in NDVI.

The NDVI signal at the Florida site appears to be an informative test of the integral method and the polynomial smoother. In some cases, multiple green-up dates in the same season and year were initially identified. For example, April 11, 1991, is the first time the target area for pixel 1 is achieved in the spring (figure 5-14). During the next period, the smoother responds to a sharp decline in NDVI (figure 5-15). The resulting negative slope of the smoother resets the program to look, when a positive slope returns, for the period at which the computed integral equals or exceeds the target area. One month is not a logical period of time between green-up dates, but three periods later, on May 9, the slope is again positive and, the integral equals or exceeds the target area (figure

5-16). Of these two green-up dates declared by this method, only the first represents a reasonable estimate because the overall trend in the data remained high in May as it approached a maximum. The inter-period variation in NDVI values at the Florida site contributed to other similar green-up declarations, of which only the first was used in this analysis.

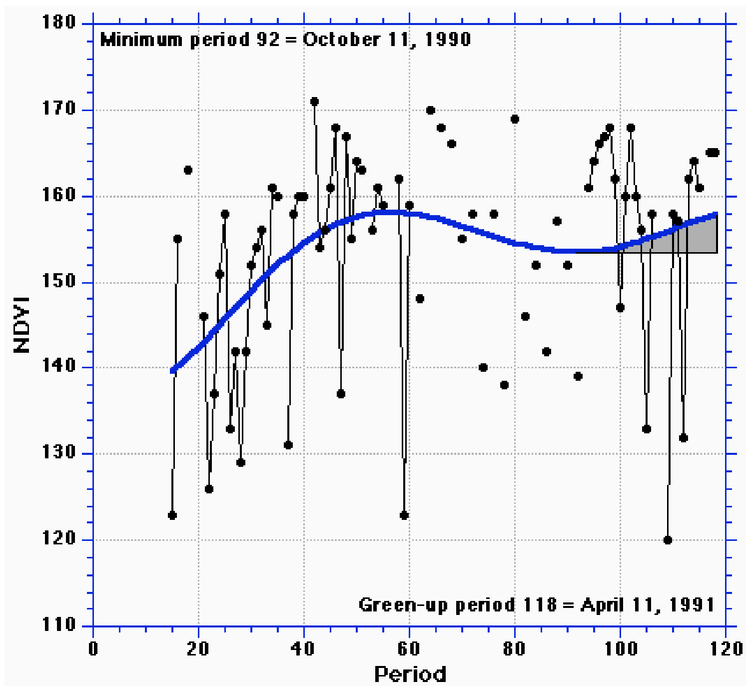


Figure 5-14. Raw and smoothed NDVI values showing the first time the target area for pixel 1 is achieved in 1991 occurs on April 11.

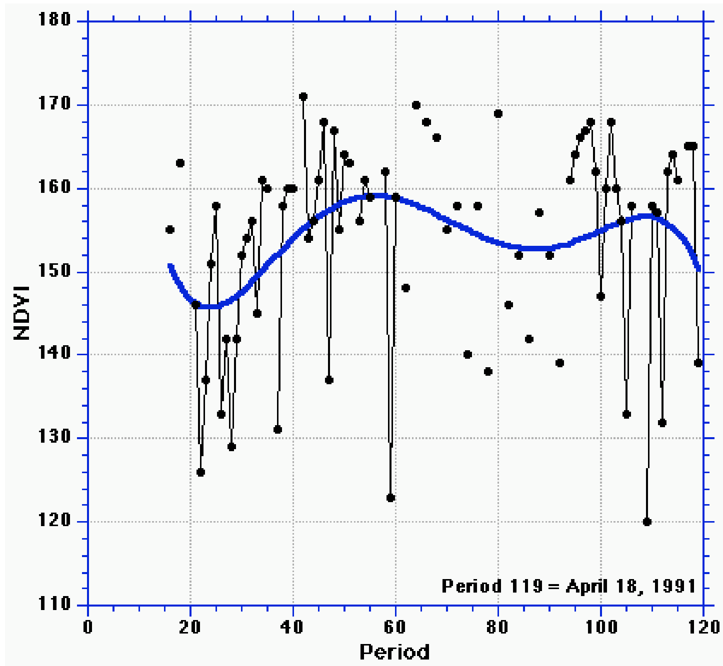


Figure 5-15. Raw and smoothed NDVI values for pixel 1 showing the declining trend in smoothed NDVI at the leading edge.

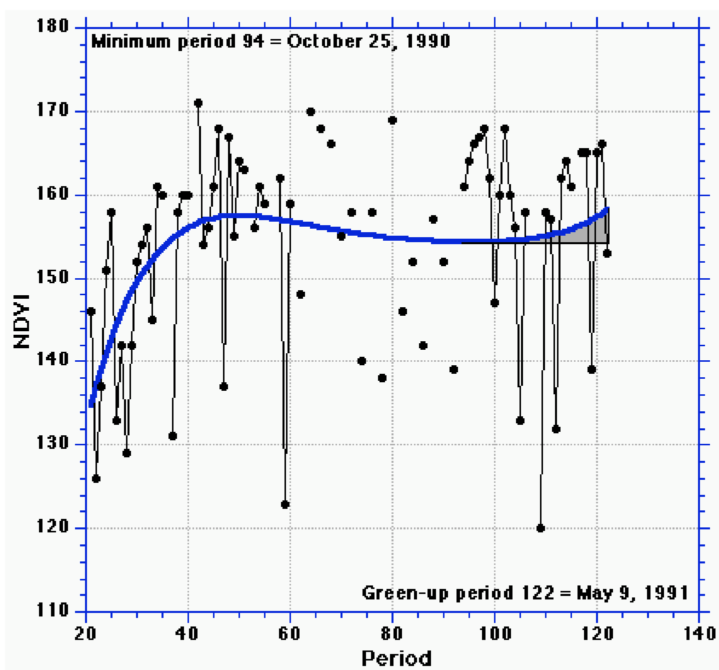


Figure 5-16. Raw and smoothed NDVI values showing the second time the target area for pixel 1 is achieved in 1991 occurs on May 9.

### 5.5 Discussion

These results reveal the strengths and weaknesses of the proposed integral method. The demonstrated strengths of the method include:

1) Applying the integral method to pixels of similar NDVI signature, classified here as difference bins, captures variation in vegetation condition at the 1-km spatial and 1-week temporal scales sufficient to discern similarities and differences in NFDRS green-up between neighboring pixels. This was the case for all three study areas.
2) The method's independence on the interannual variability is shown by the identification of green-up dates during the time of greatest increase in NDVI for each of 11 or 12 years in three locations representing three distinct NDVI climatologies.
3) The method performs as it would in an operational setting, without knowledge of the annual NDVI maximum.
4) A new process should be able to reproduce the results of the current process of ocular estimation. The integral method can reproduce green-up dates determined by the current system, thereby producing the same fire danger ratings. This was demonstrated with the California study area results.
5) The integral method can identify historical green-up dates as supported by the computation of fire danger ratings from archived weather records as shown by the results from California and Nevada.

6) The method can identify green-up dates at various times of the year: early spring in Nevada, late spring in California, and fall or spring in Florida.
7) The method can identify multiple green-up events in the same year, as shown by the Florida results.

Results also highlighted the weaknesses of the method:

1) One disadvantage of the integral method is that it assumes the measures of NDVI for each new year fall within the climatology of NDVI used to develop the target area. More years of data will alleviate this limitation to some extent, but anomalous years that deviate from average values are always possible. In the mean time, the integral method should be applied with this limitation understood and the opportunity for the user to make any appropriate adjustments to declared green-up date. This is more likely to be of concern for applications of this method to gridded computations of fire danger. The increased spatial scale and expected user interface for conversions of green-up dates from this method to point estimates should mitigate this concern in the near term.
2) The approach to determining the target area needs to be flexible enough to apply to climatologies whose minima occur near the beginning or end of the calendar year. This was not the case with Pixel 3 of the Nevada location. The climatological minimum was not anticipated to occur at the end of the calendar year. This situation is readily solved by employing a flexible window for computing the climatology, as discussed in section 5.4.2.

# Chapter 6 Summary and Applications

## 6.1 Summary

The purpose of this study was to address the need for an objective approach to declaring green-up for the National Fire Danger Rating System. The objectives were to develop a method using NDVI that could be applied operationally and to reproduce historical green-up dates for historic analysis purposes.

The proposed method is the integration of area under a smoothed curve of NDVI from the curve minimum until the climatological $NDVI_{0.5}$ target area is achieved. The integral method is based on the $NDVI_{0.5}$ technique of White et al. (1997), but modified to allow for operational usage.

One smoother was presented to illustrate the role of a smoother to fit a line to the NDVI trend for the purpose of computing the integral. The method is not dependent on the use of a particular smoother, but the smoother compute estimates for missing values and provide reasonable treatment of the leading edge of the data. Missing data are a limitation and a reality of the current data set. When data are missing during the time of green-up, the identification of this event may be delayed, but it can still be determined once actual measures return. Choice of smoother may impact the number of periods used in the analysis. The number of periods used here, 104, was chosen to mitigate the exaggeration of the smoother.

This method was tested in three locations in the US representing important and distinct NDVI signals. The method produces green-up dates appropriate for NFDRS as evidenced by the unique and reasonable dates designated for the three areas. Determination of green-up dates at 1-km resolution requires a unique target area based on the annual NDVI climatology of each individual pixel.

## 6.2 Applications with NFDRS

There are several opportunities for implementing this method into NFDRS.

### 6.2.1 Accumulate Gridded Green-up Dates for Point Estimates

In the near term, the method can be used by the local fire manager to turn on the green-up switch in NFDRS-as-we-know-it. The only difference from current NFDRS calculations would be the manager's rationale for declaring green-up. The rationale would be primarily based on satellite observations of vegetation condition rather than visual estimates or other considerations unrelated to live fuel condition. The rest of the live fuel moisture model would remain the same. Choice and selection of fuel models would not change. Fire danger ratings would remain as point data estimates for relatively large rating areas.

To incorporate 1-km-scale data into the point data approach of NFDRS, pixels should be aggregated to produce a single green-up date for each fuel model in the area represented by the fire weather station (e.g. a fire danger rating area). Green-up could be declared for each fuel model at a weather station when a user-defined percentage (e.g. 50%) of pixels representing the appropriate fuel model have cumulatively (not necessarily all in the same week) reached green-up. What is required is very similar to the current situation a manager faces - one statement of an aggregated green-up for an area that may experience green-up over a period of several weeks. Tracking each pixel allows the fire manager to “visualize” the entire rating area to make this decision. The declaration of green-up can be made at the manager’s discretion; for example, when the majority of pixels located in the areas of greatest concern to the manager are in green-up. To facilitate this application of the integral method, a process would have to be developed to collect weekly NDVI values, determine pixels entering into green-up each week, tabulate or display the accumulated percentage of pixels in green-up, and notify the manager of any recommended switch to green-up for each fuel model in each rating area.

### 6.2.2 Develop Green-up Maps and Data Layers

Weekly maps of the US or a regional area can display those pixels that have declared green-up during each successive week. The annual series of 52 images can be archived for future applications, such as 1) an animated loop of green-up in an area and 2) the weekly data layers of green-up date for future spatial analysis applications of fire danger rating. These maps can also be developed for each week of the period-of-record for historical NDVI data (1990-present).

### 6.2.3 Establish Historical Green-up Dates

The method can be used to establish historical green-up dates for existing fire weather stations for use in historical analyses of NFDRS outputs and fire occurrence. This would require 1) an effort to determine the annual aggregate green-up dates based on pixels representing the rating area of each weather station; 2) a method to import these dates into analysis software and/or fire weather databases; 3) modification of analysis software such as FireFamily Plus to accept and manipulate historical annual green-up dates for weather stations. Currently FireFamily Plus recognizes a single climatological green-up date for all years in the station record.

### 6.2.4 Integrate into 1-km NFDRS Calculations

In the long term, the integral method could be part of the calculations of fire danger ratings at a 1-km pixel scale. This application may need to be accompanied by further study of how to use NDVI to declare or replace the other herbaceous stages of the NFDRS live fuel moisture model (i.e. transition, cured, frozen, pre-green). The NFDRS-of-the-future could apply this method in either of two ways:

1) Results trigger a management decision to declare green-up for all appropriate pixels or aggregates of pixels. This preserves the “human experience” quality data check that is built into today’s NFDRS.

2) Alternatively, the NDVI-derived green-up dates (and possibly other herbaceous stages) could be enabled to function automatically with a built-in data quality routine designed to engage the "human experience".

## 6.3 Operational Considerations

### 6.3.1 Missing Data

The impact of declaring green-up only when data are available for at least analysis period 103 and 104 (the two points on the leading edge of the real-time curve) is that green-up can not be declared while pixels are obscured by cloud cover. The possible delay in green-up date discovery could be several weeks depending on the length of missing data. Once data are available for determination of the boundary NDVI trend, the green-up period must be identified in its appropriate week of the year, which would not necessarily be the most recent week with non-missing values. (The program developed for this study to estimate green-up dates does not have this feature.) This is simply a limitation of NDVI data that will be an operational reality. Estimating missing values may work for some pixels, such as those at the California site with little variation in signal, but could be misleading for pixels with greater inter-annual variation, such as at the Nevada and Florida sites. Even for the California pixels, however, applying estimates for missing data is not likely to happen operationally.

6.3.2 Smoother

More exploration of smoothers appropriate for this method is warranted. How the smoother handles missing values and end point events is very important. For example, at the Florida study area, the performance of the smoother at the edge of the data series contributed to the method describing multiple green-up periods in the same season of the year. Ideally, the smoother would have local-weight properties to avoid exaggeration at the end point and during periods of missing values.

In the case of the polynomial smoother used in this analysis, the weight or degree of the smoother is also important. Results from the California study area offer an example. Figure 6-1 shows the 5-degree polynomial smoothed 52-period climatology synchronized with the springtime leading edge of 104-period smoothed values for seven years at pixel 5. The same shift occurs at all nine pixels: the climatological minimum NDVI occurs at period 7; the $NDVI_{0.5}$ occurs at period 17 or 18 ($Period_{0.5}$). Thus, 10 or 11 weeks are necessary to reach the target area, on average. When the integral method is applied to each individual year, the minimum NDVI period is 2-5 periods later and the time necessary to achieve the target area ($Period_{green\text{-}up}$) is 2-3 weeks longer. The result is a distribution of estimated green-up dates about their climatology ($Period_{green\text{-}up}$ - $Period_{0.5}$) that is skewed to the right about 4 weeks (figure 6-2).

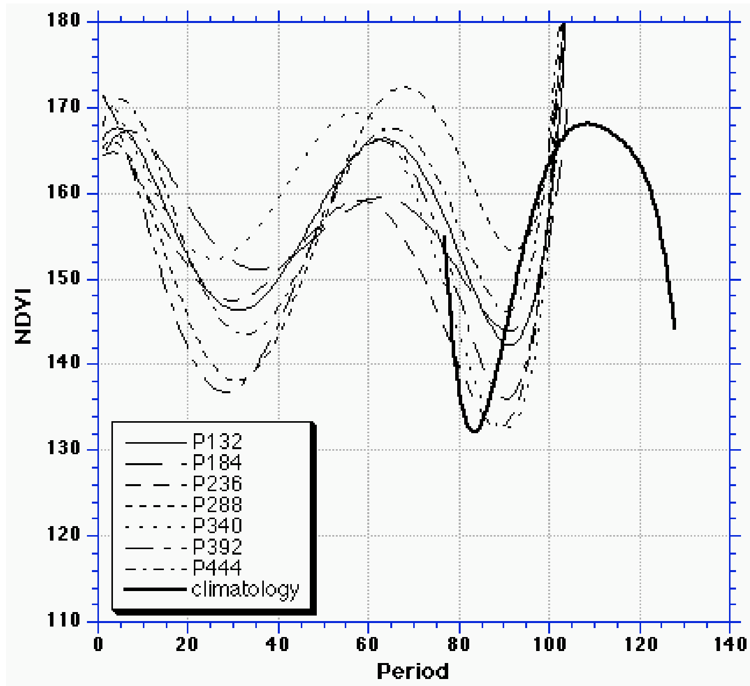


Figure 6-1. Synchronized 5-degree polynomial smoothed NDVI values for 52-period climatology and seven 104-period time-series ending at period 132, 184, etc.

This shift does not occur with the data at the Florida or Nevada study areas and is not an issue with the method, but rather with the smoother. The California site represents pixels with more variation in NDVI signal from minimum to maximum (difference bin 40) relative to the other two study areas. A higher degree of the polynomial is necessary to capture the rapid and substantial change in the NDVI. When a 7-degree polynomial is applied to the climatological and annual data in figure 6-1, the smoother more successfully describes the minimum NDVI events and removes the effect of shifting the minimum (figure 6-3).

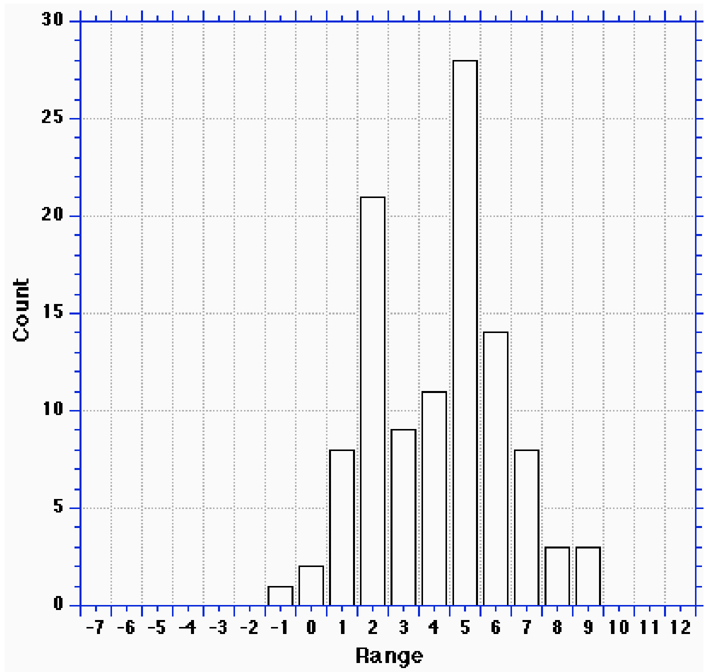


Figure 6-2. The distribution of estimated green-up dates about their climatology for California pixels using a 5-degree polynomial smoother.

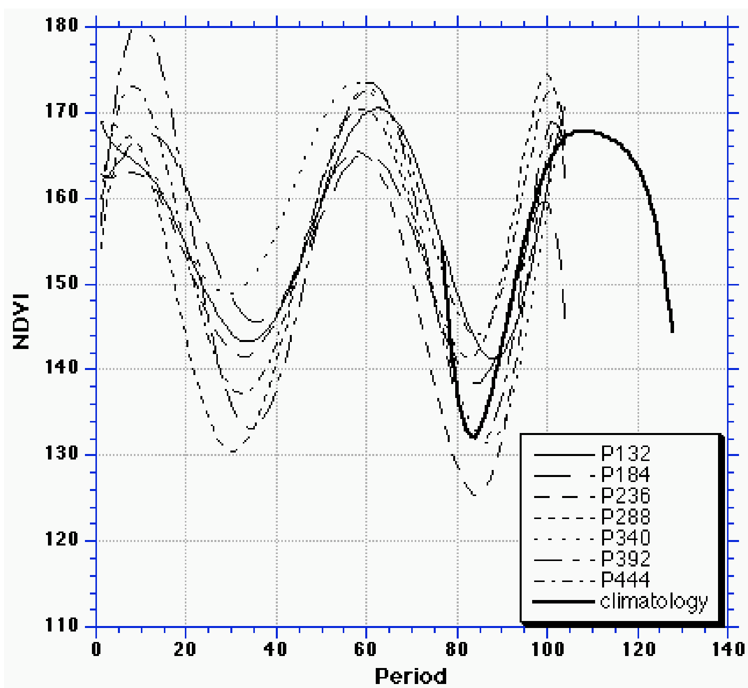


Figure 6-3. Synchronized 7-degree polynomial smoothed NDVI values for 52-period climatology and seven 104-period time-series ending at period 132, 184, etc.

### 6.3.3 Fuel Model Map

Twenty current condition cover types are classified to the same pixels as fuel model T, raising questions about the underlying variability of the NFDRS fuel model map. Cover types common to arid landscapes such as desert shrub, other shrub, pinyon-juniper, and grassland would be expected. However, moist climate cover types such as redwoods and water were also present in this fuel model classification. Although fuel models and cover types are not the same descriptions of vegetative conditions, these extremes are not readily understood. Users of the fuel model map should have the flexibility to modify it to meet the needs of their application of NFDRS fuel models. In its current form, it should be used for low-resolution applications that do not need to understand details of individual pixels.

## 6.4 Conclusion

A new method has been developed that uses NDVI to derive green-up dates for the National Fire Danger Rating System. With some further work, this method could be utilized in the operational, day-to-day processing of fire danger ratings, both in the short and long term evolutions of NFDRS. This work primarily involves integrating the method into the planning and operational processes that are necessary to compute fire danger at the local level. Training or “technology transfer” will be necessary for its implementation to be fully successful.

This new method is also capable of generating historical green-up dates for fire weather stations, which will allow for the first time an objectively produced data set of green-up dates for all years for any pixel location. More work is necessary to handle the data computational processing and connect the results to desired analysis tools, but a basic method is now available.

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# Appendix A

NFDRS Fuel Models (Deeming et al. 1977)

| Fuel Model | Description |
|---|---|
| A | Western annual grasses |
| B | Mature brush, chaparral |
| C | Open pine stands with grass understory |
| D | Southern Rough |
| E | Hardwood litter (Fall) |
| F | Intermediate brush |
| G | Over mature short-needled conifers with heavy dead fuel load |
| H | Healthy short-needled conifers with sparse surface fuels |
| I | Heavy slash |
| J | Medium slash |
| K | Light slash |
| L | Western perennial grasses |
| N | Sawgrass |
| O | High pocosin |
| P | Southern long-needled pine |
| Q | Black spruce |
| R | Hardwood litter (Summer) |
| S | Tundra |
| T | Sagebrush with grass understory |
| U | Western long-needled pine |

# Appendix B

Phenology records were requested but not available from the following research facilities:

Blodgett Forest, California
Riverside Fire Lab, California
Tall Timbers, Florida
Boise Basin Experiment Forest, Idaho
Priest River Experiment Forest, Idaho
Coram Experiment Forest, Montana
Coweeta Hydrologic Lab, North Carolina
H.J. Andrews Experiment Forest, Oregon
Eastern Oregon Agriculture Research Center, Oregon
Great Basin Experiment Range, Utah

# Appendix C

NFDRS weather stations are listed below if they had at least one green-up related issue appearing in its WIMS station catalog in 2001 and/or 2002. Stations are listed numerically and by state: the first two numbers of the six-digit station number refers to the alphabetical rank of each state (02 = Arizona). The categories correspond to those described in the following table and the discussion in chapter 2.

| Category | Green-up Issue |
|---|---|
| 1 | Green-up date is identical to neighbor station(s) |
| 2 | 2002 green-up date is identical to 2001 green-up date |
| 3 | No entry or logical date set well after actual event |
| 4 | Herbaceous stage is not logical |
| 5 | Herbaceous stage is not functioning |

| Station Name | Number | Category |
|---|---|---|
| Heber | 20301 | 1, 3, 4 |
| Lakeside | 20303 | 1, 3, 4 |
| Limestone | 20309 | 3 |
| Mountain Lion | 20310 | 3 |
| Alpine | 20401 | 1, 3, 4 |
| Iron Springs | 20501 | 3, 4 |
| Crown King | 20502 | 3, 4 |
| Verde | 20503 | 3, 4 |
| Stanton | 20509 | 4 |
| Cherry | 20511 | 3 |
| Hilltop | 20609 | 3 |
| Columbine | 21005 | 1, 4 |
| Dry Lake | 21009 | 3 |
| Trail Cabin | 21105 | 3, 4 |
| Sells | 21209 | 3 |
| Carr | 21411 | 1, 4 |
| | | |
| Ship Mtn LO | 40105 | 1 |
| Callahan GS | 40204 | 1 |
| Oak Knoll | 40218 | 1, 3, 4 |
| Round Mountain | 40221 | 3 |
| Weed | 40228 | 1, 3, 4 |
| Somes Bar | 40231 | 1, 3 |
| Indian Well | 40233 | 3 |
| Collins Baldy LO | 40237 | 1, 3, 4 |
| Quartz Hill | 40239 | 1, 3, 4 |

| | | |
|---|---|---|
| Juanita | 40240 | 2, 3, 4 |
| Brazzi Ranch | 40242 | 1, 3, 4 |
| Van Bremmer | 40243 | 1, 3, 4 |
| Canby | 40303 | 1, 3 |
| Devils Garden | 40309 | 1 |
| Rush Creek | 40312 | 1, 3 |
| Big Hill | 40402 | 3 |
| Schoolhouse | 40425 | 4, 5 |
| Weaverville | 40510 | 2 |
| Scorpion | 40517 | 1 |
| Backbone | 40518 | 1 |
| Sugarloaf | 40614 | 1 |
| Summit - Hat Mtn | 40633 | 3 |
| Oak Mtn | 40635 | 1, 2, 3 |
| Oak Bottom | 40636 | 3, 4 |
| Bogard | 40703 | 1 |
| Laufman | 40709 | 4, 5 |
| Westwood | 40719 | 1 |
| Grasshopper | 40721 | 1 |
| Corning | 40814 | 5 |
| Lassen Lodge | 40815 | 5 |
| Thomes Creek | 40816 | 5 |
| Chester | 40904 | 1 |
| Boonville | 41001 | 5 |
| McGuires | 41017 | 5 |
| Sacramento NWR | 41102 | 5 |
| Bangor | 41201 | 3, 4 |
| Carpenter Ridge | 41213 | 4, 5 |
| Saddleback | 41304 | 3, 4, 5 |
| Stampede | 41804 | 1 |
| WhiteCloud | 41806 | 1 |
| Dorris Ranch | 41807 | 4, 5 |
| Secret Town | 41808 | 4, 5 |
| Duncan Peak | 41901 | 3 |
| Lincoln | 41907 | 4, 5 |
| Foresthill 2 | 41908 | 1 |
| Beaver | 42601 | 1, 3 |
| Bald Mtn | 42603 | 1, 3 |
| Meyers | 42607 | 1, 3 |
| Hell Hole | 42608 | 3, 4, 5 |
| Mallory Ridge | 43011 | 3 |
| Mt Diablo | 43012 | 3 |
| Esperanza | 43208 | 2 |
| LaHonda | 43304 | 4, 5 |
| Spring Valley | 43308 | 3 |
| Oakland North | 43402 | 3, 4 |

| | | |
|---|---|---|
| Oakland South | 43403 | 5 |
| Toulme | 43611 | 3 |
| Wwolf | 43612 | 3 |
| Benton | 43708 | 4, 5 |
| Crestview | 43709 | 3 |
| Rock Creek | 43710 | 4, 5 |
| Corralitos | 43802 | 4, 5 |
| Ben Lomond | 43809 | 5 |
| Los Altos | 43912 | 3 |
| Poverty | 43914 | 3 |
| Mariposa | 44106 | 4, 5 |
| Mgrove | 44113 | 3 |
| NorthFork | 44204 | 4, 5 |
| Batterson | 44207 | 4, 5 |
| Devils Postpile | 44208 | 3, 4 |
| Metcalf Gap | 44209 | 4, 5 |
| Pinnacles | 44410 | 3 |
| FenceMdw | 44503 | 4, 5 |
| MtRest | 44505 | 4, 5 |
| Trimmer | 44510 | 4, 5 |
| Dinkey | 44521 | 2, 3 |
| Shaver | 44522 | 3 |
| Park Ridge | 44713 | 2, 3 |
| Cedar Grove | 44719 | 1, 3, 4, 5 |
| Shade Quarter | 44724 | 3 |
| Rattlesnake | 44728 | 1, 2, 3, 4 |
| Sugarloaf | 44729 | 1, 2, 3, 4 |
| Fountain Sprngs | 44731 | 3 |
| Wolverton | 44732 | 1, 3, 4, 5 |
| Owens Valley | 44803 | 4, 5 |
| Oak Creek | 44804 | 4, 5 |
| Panamint | 44806 | 3 |
| Mohave River Sink | 45122 | 3 |
| Boron | 45123 | 3 |
| Granite Mtn | 45124 | |
| Burns Cyn | 45125 | 3 |
| Opal Mtn | 45127 | 3 |
| Mid Hills | 45128 | 3 |
| Horse Thief Spring | 45129 | 3 |
| Los Prietos | 45203 | 4 |
| Santa Cruz Island | 45216 | 3 |
| Santa Rosa Island | 45217 | 3 |
| Vandenberg | 45219 | 5 |
| Ojai | 45315 | 3 |
| Camp 9 | 45441 | 5 |
| Rice Valley | 45620 | 3 |

| | | |
|---|---|---|
| Pine Hills FS | 45711 | 3, 4 |
| Potrero | 45730 | 4, 5 |
| Bell Canyon | 45735 | 3, 4 |
| Fremont Canyon | 45736 | 3, 4 |
| San Miguel | 45737 | 3, 4 |
| Fish Creek Mtn | 45802 | 3 |
| | | |
| Ladore | 50104 | 4, 5 |
| Great Divide | 50106 | 4, 5 |
| Porcupine | 50406 | 3 |
| Pinto | 51402 | 4, 5 |
| Hunter Creek | 51406 | 4, 5 |
| Dragon Road | 51407 | 4, 5 |
| Ernie Gulch | 51408 | 4, 5 |
| Bailey | 52001 | 1, 3 |
| Jay | 52704 | 3, 4 |
| Taylor Park | 52812 | 3, 4 |
| Huntsman | 52813 | 3, 4 |
| Red Deer | 52902 | 1, 3 |
| Lake George | 53002 | 3 |
| Cheesman | 53102 | 3 |
| Fort Carson | 53603 | 3 |
| Sanborn Park | 53804 | 3, 4 |
| Cottonwood | 53805 | 3, 4 |
| Black Canyon | 53806 | 3, 4 |
| Nucla | 53807 | 3, 4 |
| Carpenter Ridge | 53808 | 4, 5 |
| Copper Gulch | 53904 | 3 |
| Willis Creek | 54801 | 3 |
| Morefield | 55706 | 3, 4 |
| Mesa Mtn | 55805 | 3, 4 |
| Sandoval Mesa | 55902 | 3, 4 |
| Pinyon Canyon | 56202 | 1, 3 |
| Cuchara | 56203 | 1, 3 |
| | | |
| Bonner | 100101 | 5 |
| Saddle Pass | 100107 | 5 |
| Priest Lake | 100204 | 5 |
| Nuckols | 100423 | 5 |
| Eagle | 100717 | 3, 4 |
| Powell | 101031 | 5 |
| Lodgepole | 101044 | 2, 5 |
| Red River | 101045 | 5 |
| Round Top | 101049 | 3, 4 |
| Pittsburg Landing | 101100 | 3 |
| Pine Creek | 101222 | 5 |

| | | |
|---|---|---|
| Ski Hill | 101223 | 1 |
| Indy | 101303 | 1 |
| Skull | 101311 | 1 |
| Leadore | 101312 | 5 |
| Ezra Creek | 101314 | 1 |
| Kriley Crk | 101315 | 3 |
| Dead Indian Ridge | 101402 | 4, 5 |
| Little Anderson | 101710 | 3 |
| Bonanza | 101801 | 1, 5 |
| Copper Basin | 101804 | 1, 5 |
| Little Creek | 101805 | 1 |
| Horton Peak | 101812 | 4, 5 |
| Challis | 101817 | 1, 5 |
| Arco | 101905 | 4, 5 |
| Mulkay | 101906 | 1 |
| Island Park | 102105 | 1, 5 |
| Gas Cave | 102106 | 4, 5 |
| Moody | 102301 | 1, 5 |
| Fleck Summit | 102802 | 5 |
| North Fork | 102903 | 5 |
| Horse Butte | 103205 | 4, 5 |
| Crystal | 103703 | 1 |
| Grace | 103902 | 1 |
| Diamond Flat | 103904 | 5 |
| Flint Creek | 104203 | 5 |
| | | |
| Big Creek Baldy | 240119 | 1, 2, 3, 4 |
| Spotted Bear LO | 240213 | 1, 3 |
| Hungry Horse RD | 240217 | 5 |
| Cyclone | 240223 | 1 |
| Rocky Boy | 240601 | 5 |
| Ft Belknap | 240705 | 3, 4 |
| Hsprng | 241211 | 2, 3, 4 |
| Ninemile | 241507 | 5 |
| Benchmark | 241901 | 5 |
| Lincoln | 241904 | 5 |
| Helena | 241907 | 5 |
| Square Butte | 242404 | 3, 4 |
| Stevi | 242904 | 1 |
| Smith Creek | 242912 | 1 |
| Ginger | 243302 | 5 |
| Porphyry | 243402 | 3 |
| Badger Peak | 243902 | 5 |
| Pryor Mountain | 245106 | 5 |
| Ennis | 245501 | 5 |
| Timbercrest | 245607 | 5 |

| | | |
|---|---|---|
| Fox Mtn | 260110 | 1, 3, 4 |
| Bluewing | 260202 | 1, 3, 4 |
| Dry Canyon | 260203 | 1, 4 |
| Morey Creek | 260204 | 1, 4 |
| Burma Springs | 260205 | 3 |
| Texas Spring | 260206 | 4 |
| Stag Mtn | 260315 | 5 |
| Siard | 260402 | 1, 3, 4 |
| Desatoya | 260503 | 1, 4 |
| Red Butte | 260504 | 1, 3, 4 |
| Beacon | 260505 | 1, 4 |
| Combs | 260601 | 1, 3, 4 |
| Coils Creek | 260603 | 1, 3, 4 |
| Brawley Peaks | 261301 | 3 |
| Pancake | 261404 | 1, 3, 4 |
| Ely RAWS | 261407 | 5 |
| Oriental Wash | 261502 | 1, 3, 4 |
| | | |
| Albino | 290102 | 4, 5 |
| Truchas | 290210 | 3 |
| Cuba | 290705 | 4, 5 |
| Tower | 290801 | 3 |
| Brushy | 291301 | 4, 5 |
| Dunken | 292302 | 3 |
| Gila Portable | 292501 | 5 |
| Las Cruces Port. | 292905 | 5 |
| Malpais | 293301 | 4, 5 |
| | | |
| Jackson County | 315902 | 5 |
| Rockingham | 318202 | 1, 3, 4 |
| Fort Bragg | 318503 | 1, 3, 4 |
| Turnbull Creek | 319302 | 5 |
| Back Island | 319402 | 5 |
| Whiteville | 319701 | 5 |
| Nature Conservancy | 319802 | 5 |
| Sunny Point | 319803 | 5 |
| | | |
| Cedar | 350215 | 5 |
| Redbox | 350718 | 2 |
| Wanderers Peak | 350726 | 3, 4 |
| Horse Creek | 350727 | 1, 3 |
| Blue Ridge | 350811 | 3 |
| Pollywog | 350912 | 5 |
| Black Mountain | 351314 | 3 |
| Minam | 351416 | 3 |

| | | |
|---|---|---|
| Cannibal | 351604 | 5 |
| Finley | 351813 | 3 |
| Boulder | 351909 | 3 |
| Yellowstone | 352024 | 1 |
| Slide | 352207 | 2 |
| Crane Prairie | 352305 | 1 |
| Fall Mountain | 352327 | 1 |
| Board Creek | 352330 | 1 |
| Keeney Two | 352332 | 1 |
| Stub Mine | 352422 | 3 |
| Sugarloaf | 352546 | 3 |
| Village Creek | 352547 | 1, 3 |
| Hawley Butte | 352549 | 1, 3 |
| High Point | 352550 | 1, 3 |
| Trout Creek | 352552 | 1, 3 |
| Brush Creek | 352553 | 1, 3 |
| Pebble | 352554 | 1, 3 |
| Fields | 352557 | 1, 3 |
| Emigrant | 352558 | 1, 3 |
| Dunes | 352559 | 5 |
| Round Mountain | 352605 | 2 |
| Cold Springs | 352701 | 1, 2 |
| Badger | 352711 | 1, 2 |
| Salt Creek | 352712 | 4, 5 |
| Bald 2 | 352813 | 3 |
| Signal Tree | 352816 | 3, 4 |
| Quail2 | 352915 | 5 |
| Lawson | 352917 | 3 |
| Red Mound | 352920 | 5 |
| Cinamon | 353031 | 3 |
| Grandad | 353036 | 1, 3 |
| Toketee | 353038 | 1, 3 |
| Buckeye | 353040 | 3 |
| Silver Butte | 353041 | 3, 4 |
| Elkton | 353042 | 3 |
| Mt Yoncalla | 353043 | 3, 4 |
| Burnt Mtn | 353044 | 3, 4 |
| Onion 2 | 353114 | 3, 4 |
| Stella | 353209 | 1 |
| Indian | 353225 | 1 |
| Calimus | 353307 | 1 |
| Chiloquin | 353310 | 1 |
| Panhandle | 353333 | 3, 5 |
| Seldom | 353339 | 1 |
| Hoyt | 353343 | 1 |
| Rover | 353345 | 3, 4 |

| | | |
|---|---|---|
| Poor Jug | 353426 | 4, 5 |
| Brown's Well | 353428 | 1 |
| Allison | 353501 | 1 |
| Riddle Mtn | 353511 | 1 |
| Wagontire | 353512 | 1 |
| Crow Flat | 353515 | 1 |
| Sage Hen | 353517 | 1 |
| Basque Hills | 353520 | 1 |
| P Hill | 353521 | 1 |
| Bald Mtn | 353522 | 1 |
| Antelope | 353524 | 1 |
| Foster Flat | 353525 | 1 |
| Moon Hill | 353526 | 1 |
| Kelsey Butte | 353613 | 1 |
| Red Butte | 353616 | 1 |
| | | |
| Caddo Lake NWR | 411901 | 5 |
| Attwater | 416601 | 3 |
| | | |
| Quilcene | 450207 | 5 |
| Owl Mtn | 450211 | 3, 4 |
| Humptulips | 450312 | 3, 4 |
| Jefferson | 450911 | 2, 3, 4 |
| Hagar | 451115 | 3, 4 |
| Sumas | 451415 | 3, 4 |
| Kidney | 451409 | 1, 3, 4 |
| Finney | 451509 | 3, 4 |
| Johnson | 451611 | 5 |
| Gold Mtn | 451613 | 1, 3, 4 |
| Lester | 451705 | 5 |
| Greenwater | 451718 | 5 |
| Fire Academy | 451721 | 5 |
| Trout | 451917 | 3, 4 |
| Orr Crk | 451919 | 3 |
| Can Crk | 451921 | 1, 3, 4 |
| Cedar | 451922 | 1, 3, 4 |
| First Butte | 452006 | 1, 5 |
| Leecher Mtn | 452020 | 1, 5 |
| Lost Lake | 452029 | 1, 5 |
| NCSB | 452030 | 1, 5 |
| Douglas Ingram R | 452035 | 1, 5 |
| Monument 83 | 452036 | 5 |
| Peony Seed Orch | 452038 | 1, 5 |
| Stehekin Landing | 452121 | 3 |
| Viewpoint | 452128 | 3 |
| Peoh Point LO | 452206 | 5 |

| | | |
|---|---|---|
| Owl Mountain | 452513 | 1, 5 |
| Brown Mtn | 452514 | 1 |
| Kettle Falls | 452916 | 3, 4 |
| Spring Canyon | 453002 | 3, 4 |
| Deer Mountain | 453412 | 3, 4 |
| Tacoma Creek | 453413 | 3, 4 |
| | | |
| Thoro | 480114 | 1, 3, 4 |
| Quad | 480115 | 1, 3, 4 |
| Rattlesnake | 480212 | 1, 3 |
| Crandall | 480213 | 1, 3, 4 |
| Eagle | 480214 | 1, 3 |
| Echeta | 480501 | 1, 3 |
| Rochelle Hills | 480502 | 1, 3 |
| Grand Teton | 480708 | 5 |
| Poker | 481003 | 1, 3 |
| Snider Basin | 481306 | 5 |
| Raspberry | 481307 | 5 |
| Half Moon | 481309 | 5 |
| Elkhorn | 481410 | 1, 3 |
| Casper Mountain | 481502 | 1, 3 |
| Fales Rock | 481504 | 1, 3 |
| Camp Creek | 482010 | 1, 3, 4 |