

*Land Surface Phenology of North American Mountain Environments Using
the Terra Moderate Resolution Imaging Spectroradiometer*

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Land surface phenology, MODIS, NDVI, NDII, start of season

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ABSTRACT

Monitoring and understanding plant phenology is becoming an increasingly important way to identify and model global changes in vegetation life cycle events. Although numerous studies have used synoptically sensed data to study phenological patterns at the continental and global scale, relatively few have focused on characterizing the land surface phenology of specific ecosystems. Mountain environments provide excellent examples of how variations in topography, elevation, solar radiation, temperature, and spatial location affect vegetation phenology. High elevation biomes cover twenty percent of the Earth's land surface and provide essential resources to both the human and non-human population. These areas experience limited resource availability for plant growth, development, and reproduction, and are one of the first ecosystems to reflect the harmful impact of climate change. Despite this, the phenology of mountain ecosystems has historically been understudied due to the rough and variable terrain and inaccessibility of the area. Here, we use two MODIS/Terra satellite 16-day products, Vegetation Index and Nadir BRDF Adjusted Reflectance, to assess start of season (SOS) for the 2007 calendar year. Independent data for elevation, slope, aspect, solar radiation, and temperature as well as longitude and latitude were then related to the SOS output. Based on the results of these analyses, we found that SOS can be predicted with a significant R^2 (0.55-0.64) for each individual zone as well as the entire western mountain range. While both elevation and latitude have significant influences on the timing of SOS for all six study areas. When examined at the regional scale and accounting for aspect, SOS follows closely with Hopkins' findings in regard to both elevation and latitude.

Dedication

To my Father- who always believed and supported me no matter if my beliefs or chosen path were different than his own.

To my Mother- who wanted more for me.

To my husband- who held strong amidst it all, and filled me with endless encouragement and most importantly with love, acceptance, and appreciation.

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As anyone who has chosen to continue their academic pursuits can tell you, your peers, who quickly become your friends, and your family, who quickly become your rock, are a priceless bunch throughout. I have to thank them all for supporting me, believing in me, and keeping me sane. I would like to specifically thank Jess Walker for all the time she spent listening, encouraging, and of course programming with me the past year and a half. Her friendship is invaluable. Most importantly I must thank my husband Brandon for just being him, my amazing, generous, and unfailingly loving best friend. My most sincere and humble thanks to you all.

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Chapter 1: Introduction and Statement of Purpose

1.1 Introduction

Monitoring and understanding vegetation phenology (Table 1.1) is becoming an increasingly important way to identify and model global change in vegetation. Because a strong correspondence exists between climate and phenological patterns in almost all ecosystems that exhibit seasonal weather variability, it is important to characterize the plant phenology of terrestrial environments world-wide (Walker 1995). The rapid increase in temperature and change in precipitation brought on by current shifts in climate patterns are significantly affecting the timing of shifts in vegetation phenophases and length of the growing season which are critical points in plant development (Ahas et al. 2002, Scheifinger et al. 2002, and Keatley et al. 2002). If the timing of environmental cues including snowmelt and spring warming, continues to change as a result of changing weather patterns, the ability of plant and animal species to acclimate or adapt could be in question.

Currently 13.4% of the Earth's land surface is in protected areas (WDPA Consortium 2006). This includes more than 100,000 National Parks and reserves that require assistance in park planning and management

(National Park Service Office of International Affairs 2007). High elevation biomes make up one-fifth of the Earth's surface, exist in a large percentage of these national parks, and provide 80 percent of fresh water used in today's society (United Nations Food and Agriculture Organization 1997 and 2002); in addition, the vegetation of these zones have limited resources available for plant growth, development, and reproduction, and are therefore considered indicator regions for climate change (White et al. 2005). Because little current knowledge exists about large-scale spatial and temporal changes in the phenological cycle of sensitive high elevation areas, they are of special interest (Prato and Fagre 2007). However, despite the importance of these mountain environments, their phenology has historically been understudied due to the rough and variable terrain and inaccessibility of the area (Pepin and Losleben 2002).

The *primary objective* of this thesis research was to investigate the use of synoptic sensors in characterizing the land surface phenology (Table 1.1) of mountain environments in the NW United States. My broad hypothesis is that land surface phenology can be used to precisely relate phenological metrics to various terrain parameters, solar radiation, and temperature in high elevation biomes. My central hypothesis states that the diverse and varied terrestrial environment of the northern, central, and Canadian Rocky

Mountains will follow Hopkins' Law of Bioclimatics which states that start of season (SOS) is delayed:

- 3.3 days for every 100 m increase in elevation
- 4 days for every one degree change in latitude northward
- 1.25 days for every one degree change in longitude westward

In order to achieve the primary objective and test the central hypothesis, 1km MODIS (Table 1.1) pixels located in five 10° by 10° tiles for the year of 2007 were collected. This area covers the central, northern, and Canadian Rocky Mountains including one study zone located in Alberta Canada, as well as zones in Idaho, Montana, Wyoming, and Colorado United States (1,018,882 km²). To complete the analysis, the following tasks I:

- 1.) Examined spatial and temporal variation in start of season (SOS) as influenced by elevation, solar radiation, slope, aspect, latitude and longitude.
- 2.) Compared temperature and SOS relationships for values extracted from SNOTEL ground based temperature observation locations across the states of Idaho, Montana, Wyoming, and Colorado.

This project is the first of its kind to characterize the current effects of elevation, latitude, solar radiation, temperature, aspect, and slope, on the land surface phenology of mountain regions. The impetus for this research was the growing concern surrounding the effect of the current rise in global temperature on mountain and alpine systems world-wide. The results from this work fill a gap in the literature regarding the phenology of these highly sensitive and important systems and aid in future studies which are needed to understand the impact of global climate change on seasonal phenology shifts.

This thesis has two additional chapters. Chapter 2 presents a review of previous work in both high elevation biomes and land surface phenology. Chapter 3 focuses on the results of this study and is written in preparation for submission to the journal *Remote Sensing of Environment*.

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Table 1.1 Definitions

Vegetation Phenology- the study of periodic lifecycle events in plants including bud burst and leaf out as related to the environment (Cleland et al. 2007).

Land Surface Phenology- the spatio-temporal study of the vegetated land surface as observed by synoptic sensors (de Beurs and Henebry 2004).

Phenophases- An observable stage or phase in the annual life cycle of a plant or animal that can be defined by a start and end point. Phenophases generally have a duration of a few days or weeks. Examples include the period over which newly emerging leaves are visible, or the period over which open flowers are present on a plant. *Note: The definition of the term “phenophase” has not yet been standardized and varies among scientists. The definition presented here reflects our usage of the term on the USA-NPN website.)*

MODIS- Moderate Resolution Imaging Spectroradiometer

Scale- in this thesis I will discuss scale in relation to large and small extent. A large scale area represents a large extent or pixel size and is normally referred to as having a coarse resolution. In return a small scale or fine resolution area would be of small extent with a small pixel size.

Local Scale- for the purpose of this research, local scale is representative of the examination of each individual study zone.

Regional Scale- refers to the examination of the western mountain range as whole.

Chapter 2: Literature Review

2.1 Introduction

Cutter et al. (2002) posed ten big questions in geography which identified areas that future studies needed to address. One of these questions, “How has the earth been transformed by human activities”, follows along with an important tradition in geography, the tradition of studying the man-land relationship (Robinson 1976). According to the current findings of the Intergovernmental Panel on Climate Change (IPCC), the world’s surface air temperature has increased an average of 0.6 °C and is expected to rise another 1.4 to 5.8 °C in the 21st century (Pachauri and Reisinger 2007). This rapid increase in global temperature is being attributed to human activity (Wang and Chameides 2007), and the effects can be seen in sea level rise, glacier decline, increased drought, shifts in the timing of the vegetative growing seasons, shifts in breeding and migration dates of animals, increased flooding and droughts, changes in freshwater supply, increases in the spread of pests and diseases, and an increase in extreme weather events (Kramer et al. 2000).

Monitoring and understanding phenology, the study of the timing of periodic events in the annual life cycles of animals and plants as influenced

by the environment (Cleland et al. 2007), is becoming an increasingly important way to identify and model global changes in both terrestrial (Delbart 2005; Cleland 2007) and marine ecosystems (Edwards and Richardson 2004; Greve et al. 2005). Recent climate change patterns have been linked to alterations in the emergence, migration, reproduction, and senescence of plants, animals, and insects. Since a strong correspondence exists between climate and phenological patterns in almost all ecosystems that exhibit seasonal weather variability it is important to characterize these environments world-wide (White 2005). Mountain and alpine ecosystems, which have limited resources available for plant growth, development, and reproduction, are indicator regions for climate change, but their phenology has historically been understudied due to the rough and variable terrain and inaccessibility of the area (Walker 1995). It is therefore important that we begin to use available tools to study spatially and temporally continuous observations of these remote ecosystems and characterize the phenology in these regions.

Spatial and temporal changes in vegetation phenology and land surface phenology are currently monitored for changes caused not only by a warming climate, but also by anthropogenic forcings. Vegetation phenology focuses primarily on the relationship between climate and the annual biotic

events of plants such as bud burst, flowering, and senescence (Zhang et al. 2003). Land surface phenology (LSP) is a relatively recent area of study which employs remote sensing techniques and uses information recorded by synoptic sensors to study the vegetated land surface over space and time (de Beurs and Henebry 2004). When deriving phenological characteristics from satellite observations the unit of analysis is no longer an individual species, but rather the characteristics of an individual pixel or group of pixels. In this way LSP differs from traditional species-centric phenology by looking at repeat observations of seasonal and inter-annual seasonal characteristics of multiple land cover types.

In recent years overcoming obstacles in remote environments has been aided by the use of satellite sensors. Imagery collected by these sensors has been very important in increasing our understanding of global phenological patterns. Two platforms commonly used in land surface phenology studies are the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS). While remote sensing techniques have provided a platform for the study of remote areas around the world (Allen and Walsh 1996; Sarmiento et al. 2004; Tommervik et al. 2004; Walsh et al 2004), there are still gaps in the knowledge of some bioclimatic zones, especially

mountainous environments that are dominated by a varying topography, steep slopes, and a variety of aspects.

2.2 Phenology

2.2.1 Introduction and History

Phenology is the study of the timing of re-occurring biological events in both plants and animals, the effect of abiotic and biotic forcings on this timing, and the relationships between timing of events within the same or different species (Leith 1974). The word phenology is derived from the Greek *phaino* meaning to show or appear. Examples of some phenological events include the emergence of spring vegetation growth, insect hatching, animal birthing, and the first appearance of migrating birds. All of these examples are important indicators of changes in the seasonality of their surroundings and can be monitored and recorded in order to understand these cycles and any trends that may be occurring. In fact, *seasonality* has been strongly associated with phenology and is used to describe cyclical variations of non-biological events and phenomenon (Leith 1974). From a phenological standpoint, ecosystem, meteorological, and atmospheric seasonality are all of primary importance for recognizing and explaining changes temporal shifts in vegetation phenophases. Examples of such seasonal events include the formation and break-up of ice on water bodies

(Schwartz 2003), shifts in annual photoperiod length (Hänninen 1991), annual hemispheric scale patterns of climatic variability like El-Nino (de Beurs and Henebry 2008), and seasonal fluctuations of carbon dioxide accumulation and output (Lintner et al. 2006).

Although historically phenology was a study observed primarily by farmers, horticulturalist, and avid naturalists, after a 1972 symposium of the American Institute of Biological Sciences, phenology studies began to grow in number and importance in both the United States and Europe (Lieth 2008). At this time, phenological research began interesting scientist and scholars from multiple disciplines including biology, ecology, and meteorology. This interest led to increased phenological research and the development and initiation of data networks worldwide. The results and success of this early work quickly allowed the study of phenology to attract widespread attention as an important element of Earth and atmospheric science applications in the late twentieth century.

The oldest phenological records probably originated in Japan in 705 AD (Menzel 2003), but modern phenological observations in East Asia really started during the 1920's in China when Dr. Kezhen Zhu began observing spring phenophases of trees and birds in Nanjing (Chen 2003). In the United States, the history of phenological studies is much shorter.

Phenological networks were not established until the 1950's when volunteers were solicited throughout 12 states to observe common purple lilac plants and two honeysuckle cultivars (Schwartz and Beaubien 2003). Despite this late start, these experimental observations, now spanning for over 40 years, provide a very relevant database of long-term records that have been used for numerous studies exploring phenological variability across the U.S. (Schwartz and Beaubien 2003).

2.2.2 Importance and Current Applications

Phenology plays an essential role in regulating the abundance and diversity of organisms and their ecological functions. Understanding the phenology of a species, an ecosystem, or even a biome, is key in understanding how a changing climate might affect such species at all these ecological scales (Bonan 2002). Appropriate timing of phenological shifts can affect whether plants and animals thrive and survive in their environments (Myneni et al. 1997; Schwartz et al. 2006; Cleland et al. 2007; Heumann et al. 2007). Since plants are finely tuned to the seasonality of their surroundings and respond to the cumulative effects of daily weather as it fluctuates over time, their developmental stages are effective indicators of a changing climate (Schwartz et al. 2004; Cleland et al. 2007). Zhang et al. (2004) and others, have shown that field observations of species level

phenophases can be used successfully to show local, regional, and global climatic variations which have occurred over the past few decades. In addition, previous studies have shown that both field observational modeling and evidence collected through remote sensing techniques can show and support a change in vegetation phenology in response to the warming weather trend that is currently present world-wide (Reed et al. 1994; Inouye 2003; Menzel 2003; White et al. 2005; Heumann et al. 2007; Inouye 2008). These changes, including an earlier arrival of spring and an increased growing season leading to a later arrival of winter, have many consequences for human health, ecological processes, and the global economy (Peñuelas and Filella 2001).

In addition to its use in climate change research and global change studies (White et al. 2005, Richardson 2007) over recent decades the study of phenology has been used to examine the effect of political change (de Beurs and Henebry 2004) and to predict agricultural yield and potential food shortages brought on by drought (Brown et al. 2006). Phenological data and models are also useful in drought monitoring, and wildfire risk assessment, as well as management of invasive species, pests, and infectious diseases. Based on this knowledge it is imperative that we begin to use available tools to create and study spatially and temporally

continuous observations of phenology world-wide. Continued communication and collaboration between the international scientific community and the general public is also an essential component to the continued establishment of long-term phenological datasets. Equally important is the recognition that research should not be restricted to the mid-latitudes where traditionally, most phenology observations have occurred (Myneni et al. 1994). High altitude and high latitude environments are especially sensitive to warming weather trends and should be considered a top priority in future studies.

2.3 Mountain Environments

2.3.1 Introduction

A mountain environment can be defined according to a number of criteria. From a visual standpoint, most cited definitions indicate that a mountain is a landform which extends above the surrounding environment forming a peak that has been molded through processes of erosion and frost (Kapos et al. 2000). Most geographers define mountains as areas which consist of a varied topography with steep slopes, frequently shifting aspects, and marked environmental gradients (Blythe et al. 2000). Cultural heritage is also a contributing factor in determining whether a landform is coined a mountain or a hill, but there are currently no universal rules regarding the

elevational requirements of either (Bernbaum 1997). Mountains occur on all continents, in all latitude zones, and within all the world's principal biome types, from hyper-arid hot desert and tropical moist forest to arid polar icecaps; they support a correspondingly wide variety of ecosystems. In recent decades a more operational quantitative definition which incorporates elements of both altitude and slope has become possible through the development and use of geographic information system (GIS) technology and digital elevation models (DEM) (Blythe et al. 2002).

Mountains are typically high energy environments that experience very unique climate patterns as well as influence regional climate due to the effect of their size and shape on circulation patterns, precipitation, and solar radiation. Four factors that work to determine the climatic characteristics within these environments are latitude, altitude, continentality, and regional circulation zones (Barry 1992; Whiteman 2000). Aspect and slope are additional factors that contribute in the creation of microclimates which can vary drastically within short distances (Whiteman 2000; Blythe 2002).

Within the Rocky Mountains, there is a classic orographic precipitation factor that generates larger levels of precipitation on the windward side of the mountain, and a rain shadow effect which creates a more arid zone on the leeward side. In most all mountain environments studies have shown

that predictable relationships can be seen between altitude, total precipitation, air pressure, humidity, wind speed and solar radiation (Barry 1992; Blythe 2002; Kittel et al. 2002). While precipitation, solar radiation, and wind speed increases as altitude increases; humidity and air pressure decrease (Hopkins 1920; Whiteman 2000; Blythe 2002; Kittel et al. 2002). In most situations it has been found that temperature and elevation also share a linear relationship with each other, in that as elevation increases temperature decreases, this relationship is defined as the environmental lapse rate, however this is not always the case (Price 1981; Barry 1992; Whiteman 2000).

Mountain environments are home to a large diversity of distinct ecosystems. The alpine ecosystems are defined as the area above the treeline (Körner 2003), and they extend over a broad range of latitudes and altitudes exhibiting distinct characteristics. One principal distinction within these ecosystems is the shortened length of the growing season which is primarily controlled by a combination of temperature and level of snowpack (Price 1990). Research has shown that time of snowmelt appears to be an almost universal effect on the phenology within high-altitude environments (Bliss 1956, Mark 1970). This variation can usually be linked to variation in accumulation and the subsequent melting of snow present

(Wagner and Reichegger 1997; Ratcliffe and Turkington 1989). Another important characteristic of alpine ecosystems is that few high altitude plants exhibit a photoperiodic response for phenological events, making them unique in the way that global climate change affects them in relation to other environments (Ives et al. 1997). Despite the uniqueness of all ecosystems found within mountain environments, the phenology of mountain areas has traditionally been understudied and the studies that do exist have been short-term and species centric (Bacher and Jeanneret 1994; Spehn and Körner 2002; Körner 2005; Ladining and Wagner 2009). Though these studies should not be discounted as they provide useful information on the spatial patterns of snowmelt and phenology on a small scale, long-term, large scale studies are required to gain a true understanding of not only the phenology of these areas, but also the effects of climate variables on the life history events of plants and animals in these regions.

2.3.2 Importance

Mountain ecosystems make up over one-fifth of the Earth's land surface spanning an area from the equator to just near the poles (Blythe 2002). In addition to the commonly known characteristics of a marked topographic variation and steep slopes, mountains are highly diverse

systems in flora, fauna, and human ethnicity, and are found on every continent at varying altitudes beginning as low as just above sea level and ranging as high as the summit of Mt. Everest.

Mountain areas provide homes to more than one-tenth of the human population (Price 1981; Fagre et al. 2003). At a global scale, mountains are a source of all the major rivers and provide over two billion people food, timber, minerals, hydroelectricity and fresh water (Körner 2005). However, the importance of a mountain ecosystem extends far beyond their local and non-local human inhabitants. Mountain biodiversity is among the highest of all ecoregions, including tropical rainforests. This is because of the extraordinary range of elevations and climates found within these systems (Ives et al.1997; Fagre et al. 2003; Körner 2005). Mountain environments are the original home of more than 30% of the plant species that supply three-fourths of the world's food. The remoteness of these rugged landscapes provides protection from depletion and extinction to many crop varieties, however changing climate patterns are having negative effects on high elevation agriculture as temperatures consistently rise, and precipitation patterns shift (Jodha 1997). Notwithstanding the general isolation of some mountain ecosystems, they are exceedingly fragile. In many parts of the world, climate change, pollution, exploitative mining,

unsustainable agriculture and tourism are all taking a toll on mountain environments, leading to widespread degradation and an increased risk of calamities such as floods, landslides, avalanches and famine (Ives et al. 1997).

Despite the importance of mountain environments, and the dependence that the world's population has on these unique areas, a very small amount of research dollars are allocated and awarded for mountain and high elevation biome research each year (Price 1990; Sphen and Körner 2002). In addition, many of these mountain areas have a large percentage of their habitat that is inaccessible due to their rough and varied terrain making it difficult if not impossible for researchers who wish to study and understand the many dynamic ecological processes. It is particularly difficult to predict the effects of altered weather patterns and climate variability in mountain ecosystems because of this diverse topography, and ecological isolation (Fagre et al. 2003).

2.3.3 Mountain Ecosystems and Phenology

Perhaps more than any other bioclimatic zones, phenological events at high altitudes and high latitudes are constrained by a short growing season delimited by colder temperature and snowpack. Wagner and Reichegger (1997) found that a north facing slope subject to deep snow

deposition took almost a month longer to melt out than sunlit spots contributing to a delay in SOS on these northerly slopes. In alpine systems, both temperate and tropical, the effects of warming can be seen in the decline of the snowpack (Nams and Freedman 1987) and the almost 20 day advancement of annual snowmelt since the 1940's (Stewart 2008).

However, in the Central Rocky Mountains a significant relationship has been found between the date of snowmelt and the abundance of summer flowering showing that a greater snowpack equals a later snowmelt, which results in a delayed SOS and a reduction in loss of buds due to frost (Inouye 2008). In addition, based on an analysis of historical data, significant 100 year positive trends have been found in the Rocky Mountains for annual and seasonal precipitation and mean temperature. In the northern and central Rockies, summer precipitation has increased by 30% and the annual mean temperature has risen by 0.2° C (Inouye 2008). An added change has been observed in the occurrence and length of thermal inversions where cold air drainages have been shown to cause a delay of 2-5 days in timing of budburst and flowering (Inouye and Wielgolaski 2003).

High latitude environments are characterized by a strong variation in the length of sunlight throughout the year. In areas north of the Arctic Circle there is sunlight 24 hours a day near the Summer Solstice, and 24

hours of darkness 6 months earlier. When the sun is prominent in these areas, the angle tends to be low in comparison to its position further south, and this different aspect of slopes strongly influences light conditions and solar radiation (Wielgolaski and Inouye 2003). Global warming is expected to lead to an increase in temperature and precipitation in the summer and winter seasons (Kramer et al. 2000; Pachauri and Reisinger 2007). Potential responses to climate change can be predicted by modeling the phenology in these areas which enable scientist and management officials to formulate appropriate strategies for future management plans.

2.4 Remote Sensing

2.4.1 Introduction, History, and Importance

Remote sensing is a practice that humans experience daily as we observe our surroundings from afar. In science, remote sensing is a method of study that employs techniques which enable the enhanced observation from a distance, of events and phenomenon surrounding us. There are numerous forms of remote sensing; the most common involves our own visual observations as we scan our environment. Other forms of remote sensing require aids such as hand held cameras, aerial based photographic equipment, and satellite sensors. By utilizing electromagnetic radiation

reflected or emitted from the object of analysis, these tools enable scientific observations of the Earth's land surface from varying spatial and temporal scales and can allow for extensive research regarding many social and biological phenomenon (Campbell 2006). In addition to Earth surface studies, satellite sensors also enable observations of the lithosphere, hydrosphere, and atmosphere which aid in studies of plate tectonic movements (Bishop et al 1998), glacial recession (Aniya et al 1996), and meteorological forecasting (Bevis et al. 1992).

In the late 1800's cameras were positioned above the Earth's surface in balloons or kites to take oblique aerial photographs of the landscape (Campbell 2006). During World War I aerial photographs were used to gather information about the positioning and movement of troops. After the war, continued remote observations were used to create topographic maps and catalogue landuse across North America. Following World War II, the development of color infrared film allowed for an even greater acquisition of information, including detailed observances on vegetation type and health. In the 1960's remote sensing was revolutionized by the deployment of satellite sensors which allowed for the observance and recording of large scale observations of scenes formerly unknown (Pidwirny 2006). Less than a decade later, the Landsat satellites were launched carrying multispectral

sensors which could gather continuous and extensive observations of areas previously unattainable enabling an unmatched opportunity for studying and monitoring global change patterns. Since the 1970's countless other satellites have been launched with exceedingly higher technological capabilities that have all contributed in furthering scientific research in a multitude of disciplines.

Remote sensing provides global, continuous observations of processes needed to understand the Earth's system as a whole. In recent years, human populations have been recognized as a driving force behind drastic changes to many elements within the Earth's biosphere (Turner and Meyer 1994). As the human population continues to expand perpetuating further land cover alterations, anthropogenic climate change, and global economic strain; research on both human induced global change as well as natural cyclical changes in the Earth's environment pose significant challenges to the scientific community (Kang et al. 2003). Physical, social, and biological scientists have been tackling the challenges of data acquisition and analysis for decades and have recognized that in order to begin to understand a system as vast and complex as the Earth, a broad-scale interdisciplinary approach to future research is paramount (Ehrlich et al. 1994). Working together scientist from multiple disciplines have

contributed an extensive body of literature which documents the development of and potential for remote sensing data analysis techniques to identify environmental concerns and to monitor physical, social, and biological processes relevant to global change research (Turner and Meyer 1991; Reed 2006; White and Nemani 2006).

2.4.2 Satellite Remote Sensing

Satellite remote sensors are a major source of consistent, continuous data for atmospheric, ocean, and land studies at a variety of spatial and temporal scales. The primary satellite sensor that has traditionally been used for global change studies is the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR). This sensor was first launched in 1978 on the TIROS-N with four channels. In 1981 the sensor increased to five channels and was launched on the NOAA-7 satellite. Since then there have been five satellites launched carrying AVHRR sensors that are important to the study of phenology (NOAA 7, 9, 11, 14, and 16). These satellites have two daily observational overpasses, an average orbital height of 830km, and two levels of spatial resolutions including 4.4km for global area coverage and 1.1km for local area coverage. While there are currently six channels, there are only two that are used in vegetation studies, band 1-Red (Daytime cloud

and surface and vegetation mapping) 0.58-0.68 μ m and band 2- NIR (Surface water, ice, snow melt, and vegetation mapping) 0.725-1.10 μ m. AVHRR-NDVI data are available in two consistently processed databases, Global Inventory Modeling and Mapping Studies (GIMMS), beginning in 1982 at an 8km global resampling grid and the Pathfinder AVHRR Land (PAL) dataset at a 1km resolution from 1989 covering the U.S. (Reed et al. 2003). Issues with AVHRR include a lack of onboard calibration, orbital drift, and limited bands for atmospheric correction. Despite some challenges, this satellite provides us with the ability to study coarse resolution satellite data since 1982 creating a long-term record for remote sensing vegetation observations.

Other moderate resolution satellites include the Moderate Resolution Imaging Spectroradiometer (MODIS). These sensors pass north to south across the equator in the morning with Terra, and south to north in the afternoon with Aqua. The Terra satellite was launched December 18th, 1999 and began recording images on the 24th of February 2000. The Aqua satellite launched May 4th 2002 and began recording images shortly after on the 24th of June. Unlike the AVHRR sensor, MODIS has a spectral resolution of 36 spectral bands and spatial resolutions of 1000m, 500m and 250m. The 250m data has two spectral bands: Red and NIR. The 500m (15

arc second) supports the first 7 bands (Table 1.1), while the 1000m (30 arc second) supports all 36 bands. MODIS tiles come in both fine and coarse resolutions. Fine resolutions are provided in a Sinusoidal projection with $10^{\circ} \times 10^{\circ}$ tiles. The coarse resolution data is used for the global climate modeling and is presented in the Climate Modeling Grid (CMG) which has a geographic projection with grid cell sizes of 0.05° (5.6km). Because of the vast number of bands provided in the MODIS sensor, a diversity of products has been developed. Two commonly used products for the study of phenology are the MODIS Land surface temperature and emissivity product, and the MODIS vegetation indices products (discussed below). The LST product provides a per pixel value for both temperature and emissivity.

MODIS provides improved geometry, radiometry, and overall data quality from that available with the AVHRR sensor. Products which aid in global change research, including the vegetation products normalized difference vegetation index and the enhanced vegetation index (NDVI and EVI), are routinely produced and offered at spatial resolutions of 250m, 500m, and 1km. These indices provide us with the ability to analyze various phenological events that are essential to recognizing and understanding disturbances in seasonality in organisms.

2.4.3 Remote Sensing and Phenology

The need for large scale phenology measurements to record and strengthen global climate change research is growing. Remote sensing allows for the analysis of large scale ecosystem function and changes, as large pixels integrate multiple species in one view. While very specific phenological events such as flowering and fruiting cannot be observed directly with coarse resolution sensors like AVHRR and MODIS, defined phenophases including start and end of season, peak photosynthetic activity, rate of green-up and senescence, and growing season length can be estimated (Heumann et al. 2007) by using one of several phenological metrics that have been developed from satellite data (White et al. 1997, Zhang et al. 2004, Delbart et al. 2005, White et al. 2009).

Most remote sensing studies that look at phenology utilize data which are collected in the red and near infrared portions of the electromagnetic spectrum. Vegetation indices, briefly mentioned above, take advantage of the spectral reflection and absorption characteristics of plants by utilizing data collected from these two bands and transforming it into a vegetation or greenness index.

The Normalized Difference Vegetation Index (NDVI) is a measure of greenness' or density of chlorophyll and leaf tissue that is calculated from

the Red and Near Infra-red spectral reflectance bands (Tucker 1979). This index has been of the most commonly used for large area studies and is calculated as follows.

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{RED}}) / (\rho_{\text{NIR}} + \rho_{\text{RED}})$$

NDVI relies on the absorption of red radiation by chlorophyll, and the scattering of near infrared radiation by the foliage. As a result of this reaction in plants, red reflectance tends to decrease as the amount of green increases. At the same time leaf area index and crown coverage are increasing causing a rise in the near-infrared surface reflectance (Figure 2.1). NDVI has been shown to be highly correlated with the fraction of photosynthetically active radiation (FPAR) absorbed by vegetation (Myneni et al. 1997). As vegetation types and characteristics vary across land cover type, the NDVI profile will change dependent on the type of land cover being examined (Figure 2.2).

While NDVI is the most commonly used index, it is sensitive to external factors not related to the canopy itself including leaf water content and snow. In addition, NDVI tends to saturate with a high leaf area index between 2 and 4. More recent studies focused on the analysis of land surface phenology have begun to include reflectance values from other portions of the visible spectrum, including the blue band, in order to

account for the interaction between snow and vegetation green-up (Delbart et al. 2005). *Delbart et al. 2005* explored the use of a combination of indices including the normalized different water index (NDWI) and the normalized different snow index (NDSI) to help eliminate the confounding effects of snow melt on the NDVI signal in boreal regions. *Delbart et al.* argue that the use of NDVI in boreal regions suffers from uncertainty based upon the fact that NDVI increases not only with green-up, but also during snowmelt, possibly leading to a misrepresented value for SOS that appears to be much earlier than actual ground based observations indicate. Other index that have been proven effective in reducing canopy background effects and atmospheric contamination are the soil adjusted vegetation index (SAVI) (Huete et al. 1988) and the MODIS enhanced vegetation index product (EVI) (Huete et al. 1994). In a comparison of SAVI and NDVI, SAVI showed itself to be very well suited to studies that are concerned with structural canopy parameters such as LAI and biomass, which are more apparent in NIR; while NDVI seems well suited for studies concerned with photosynthetic capacity of vegetation cover (Reed et al. 2003). EVI can also be used as a replacement for NDVI because it reduces sensitivity to soil and atmospheric effects while remaining sensitive to variation in canopy density (Zhang et al. 2004). NDVI still continues to be

the standard for large scale phenology studies primarily because it can be created based on data from both the AVHRR and MODIS satellite sensors.

Numerous phenological metrics derived from satellite data are available and offer different ways of operationalizing annual phenological metrics (Zhou et al. 2001; Zhang et al. 2003; Delbart et al. 2005). Unlike ground-based studies, when deriving phenological characteristics from remote sensors' the object is no longer the species or even the community, but rather the characteristics of individual pixels, thus depending on the size of the pixel, the object of analysis can become the characterization of the phenology of a mosaic of several land cover types. Metrics commonly used for land surface phenology analysis are based on remotely sensed image time series of vegetation indices (VI) and aim to show seasonal events including onset of leafing, arrival of senescence, and timing of the maximum photosynthetic activity as indicated by the maximum NDVI value (de Beurs and Henebry 2004). Multiple techniques have been developed and continue to be refined to aid in the measurement of these annual phenological events as collected from satellite observed data (Figure 2.3). Within the diversity of satellite measures and methods there are four main categories: Statistical Models; Derivatives, Smoothing Algorithms, and Thresholds (de Beurs and Henebry 2008). Comparative studies of these

various methods found that SOS estimates can vary extensively among methods dependent on implementation and ecoregions (White et al. 1997; Schwartz et al. 2002; Reed et al. 2003). While selecting the most appropriate method is difficult without additional ecosystem information, the use of local thresholds based on variations of an $NDVI_{ratio}$ (discussed below) has been shown to be among the better methods used to estimate SOS dates that consistently corroborate ground-based phenology data (White et al. 2009).

Thresholds are considered one of the simplest methods used to determine the start and end of season. However, a simple threshold method, where a threshold value is set to an arbitrary value, can be inconsistent when applied on a large spatial scale. A more commonly used threshold method is based on NDVI ratios which control for this error by transforming the NDVI value to a ratio ranging from 0-1. The formula follows:

$$NDVI_{ratio} = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

Here the start of season (SOS) is determined as the day that the NDVI ratio rises past a designated percent threshold mark, and the end of season (EOS) is stated to be the day at which the NDVI ratio falls past that same percent mark (White et al. 1997). For this method 50% is the most widely chosen

value as it is believed that this threshold is indicative of the most rapid vegetation growth of the season (Figure 2.4). However, some researchers still choose to opt for a lower percent threshold value as they feel that the first appearance of spring foliage is important because it may reflect the strongest response to temperature change and therefore be a crucial measure for assessing various processes related to important phenological metrics including (SOS) and duration of the growing season (Schwartz et al. 2006).

Researchers are still attempting to form a consensus on which method provides the most accurate estimations for annual phenological events; however it may be most practical to use multiple methods dependent on the variability of your study area (White et al. 2009).

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Figures and Tables

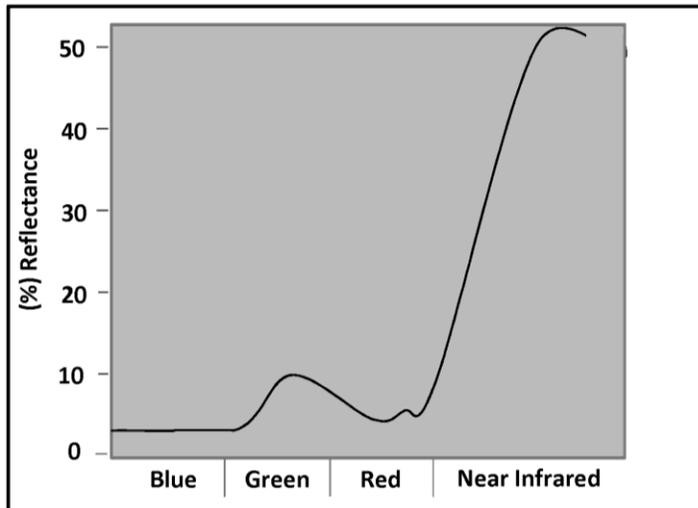


Figure 2.1 Typical reflectance emitted by living vegetation. As light is absorbed in the blue and red regions of the visible spectrum, green shows the highest percent reflectance. When you add regions outside of the visible spectrum you find that the reflectance value is brightest in the near infrared. These values will increase during the growing season and will decrease again during vegetation senescence.

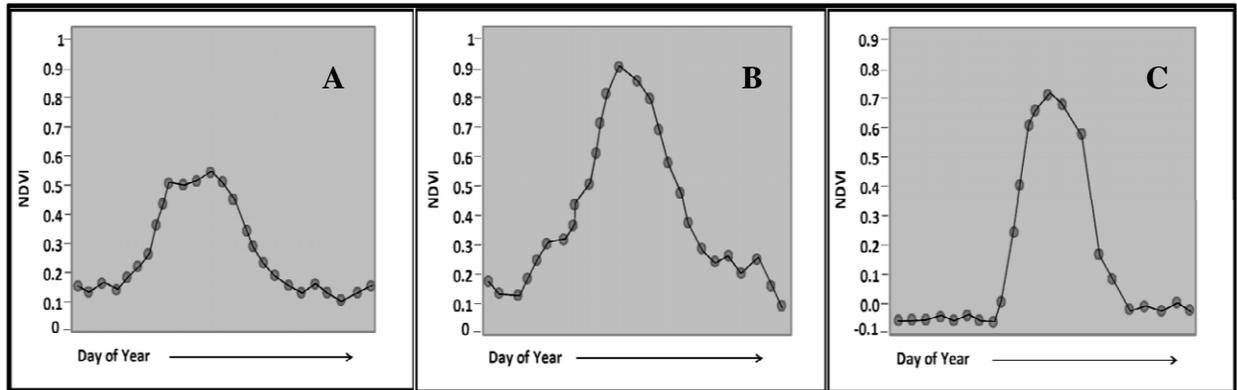


Figure 2.2 Variation in the NDVI profile of three different land cover types over an annual cycle. A) represents a forested pixel in Montana. B) represents an agricultural zone in central Illinois where the crop sampled is corn. C) represents a pixel located over a tundra region in northern Alaska.

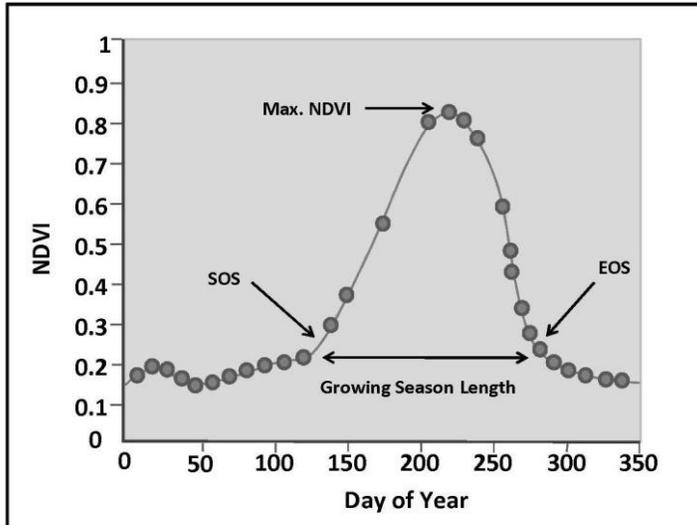


Figure 2.3 The NDVI profile of vegetated pixels can be used to examine the onset or transition of numerous phases throughout the phenological cycle. This graph represents a clean NDVI signal for an entire year and indicates the observation at which SOS, EOS, and maximum photosynthetic activity occurred, as well as gives the estimated length of the growing season based on start and end of season.

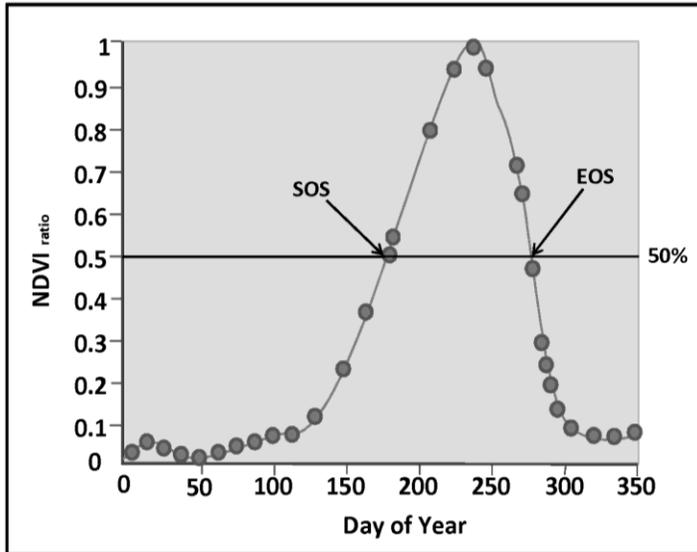


Figure 2.4 This graph represents a NDVI signal for an entire year. When the threshold based on $NDVI_{ratio}$ model is applied start of season (SOS) is estimated to be the point at which the NDVI signal surpassed 50% of its total range. End of season (EOS) is estimated as the point when NDVI drops back passed the 50% mark.

Table 2.1 *The Moderate- Resolution Imaging Spectroradiometer has a total of 36 bands. The first seven are primarily used for land, cloud, and aerosols boundaries. This table gives the bandwidth and observed spectrum color of these seven bands.*

| Band | Bandwidth(m) | Spectrum Color |
|-------------|---------------------|-----------------------|
| 1 | 620-670 | Red |
| 2 | 841-876 | NIR |
| 3 | 459-479 | Blue |
| 4 | 545-565 | Green |
| 5 | 1230-1250 | MIR |
| 6 | 1628-1652 | Beyond MIR |
| 7 | 2105-2155 | Beyond MIR |

Land Surface Phenology of North American Mountain Environments Using the Terra Moderate Resolution Imaging Spectroradiometer

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Abstract

Monitoring and understanding plant phenology is becoming an increasingly important way to identify and model global changes in vegetation life cycle events. Although numerous studies have used synoptically sensed data to study phenological patterns at the continental and global scale, relatively few have focused on characterizing the land surface phenology of specific ecosystems. Mountain environments provide excellent examples of how variations in topography, elevation, solar radiation, temperature, and spatial location affect vegetation phenology. High elevation biomes cover twenty percent of the Earth's land surface and provide essential resources to both the human and non-human population. These areas experience limited resource availability for plant growth, development, and reproduction, and are one of the first ecosystems to reflect the harmful impact of climate change. Despite this, the phenology of mountain ecosystems has historically been understudied due to the rough and variable terrain and inaccessibility of the area. Here, we use two MODIS/Terra satellite 16-day products, Vegetation Index and Nadir BRDF Adjusted Reflectance, to assess start of season (SOS) for the 2007 calendar year. Independent data for elevation, slope, aspect, solar radiation, and temperature as well as longitude and latitude were then related to the SOS output. Based on the results of these analyses, we found that SOS can be predicted with a significant R^2 (0.55-0.64) for each individual zone as well as the entire western mountain range. While both elevation and latitude have significant influences on the timing of SOS for all six study areas. When examined at the regional scale and

accounting for aspect, SOS follows closely with Hopkins' findings in regard to both elevation and latitude.

3.1 Introduction

According to the current findings of the Intergovernmental Panel on Climate Change (IPCC), the world's surface air temperature has increased an average of 0.6 °C since the 1950's and is expected to rise another 1.4 to 5.8 °C in the 21st century (Pachauri and Reisinger 2007). Effects of this rapid increase in global temperature can be seen in both marine and terrestrial environments at all latitudes and longitudes through sea level rise, glacier decline, increased drought, shifts in the timing of the vegetative growing seasons, shifts in breeding and migration dates of fish and land animals, increased flooding, and an increase in extreme weather events (Kramer et al. 2000).

Phenology, the study of periodic lifecycle events in plants and animals as influenced by their environment, plays an essential role in regulating the abundance and diversity of organisms and their ecological functions. Timing of phenological events can affect whether plants and animals thrive and survive in their environments (Myneni et al. 1997; Schwartz et al. 2006; Cleland et al. 2007; Heumann et al. 2007). Because plants are finely tuned to the seasonality of their surroundings and respond

to cumulative effects of daily weather as it fluctuates over time, their developmental stages are effective indicators of a changing climate (Schwartz et al. 2006; Cleland et al. 2007). Previous studies have shown that rapid increases in temperature and change in precipitation brought on by current shifts in climate patterns can be directly linked to alterations in the timing of phenological processes, including a significant effect on the date of spring green-up, maximum photosynthetic activity, and length of the growing season, which are critical points in plant development (Ahas et al. 2002; Scheifinger et al. 2002; and Keatley et al. 2002) as well as determinants in levels of integrated CO₂ uptake (Baldocchi et al. 2001) and transpiration (Wilson and Baldocchi 2001). If the timing of environmental cues continues to change as a result of changing weather patterns, the ability of plant and animal species to acclimatize could be in question. This strong correspondence between climate and phenological processes can be found in almost all ecosystems exhibiting seasonal weather variability, thus it is important to characterize the phenology of terrestrial environments world-wide (Walker, 1995).

Mountain and alpine ecosystems cover more than twenty percent of the Earth's land surface spanning an area from the equator to just near the poles (Price 1990). In addition to the commonly known characteristics of a

marked topographic variation resulting in steep slopes and varied aspects, mountains are highly diverse systems in flora, fauna, and human ethnicity, and are found, at varying altitudes, on every continent. These regions are typically high energy environments which provide 80 percent of fresh water used in today's society (United Nations Food and Agriculture Organization 1997 and 2002) and experience unique climate patterns aiding in the creation of niche vegetation zones limited in resources available for plant growth, development, and reproduction (White et al. 2005). In many parts of the world, climate change, pollution, exploitative mining, unsustainable agriculture, and tourism all take their toll, leading to widespread degradation of these environments and an increased risk of calamities such as floods, landslides, avalanches, and famine (Ives et al. 1997). Despite the importance of mountain environments, their phenology has historically been understudied due to the rough and variable terrain and inaccessibility of the area (Pepin and Losleben 2002). The difficulty presented by such an environment leads to gaps in the literature regarding many dynamic ecological processes including the flow of water, nutrients, and energy which must be understood at both local (community and ecosystem level) and broad (continental or even global) scales in order to grasp the consequences of continued anthropogenic damage (Fagre et al. 2003).

In recent years monitoring of remote environments has been aided by the use of satellite sensors. Imagery collected by these sensors have been important in increasing our understanding of global phenological patterns and provide one of the best forms of documenting and studying temporally continuous observations at numerous scales and spatial locations. Land surface phenology uses information recorded by synoptic sensors to study the vegetated land surface over space and time (de Beurs and Henebry 2004). Vegetation indices (VI) produced from reflectance data collected by the moderate resolution imaging spectroradiometer (MODIS) quantifies the concentrations of green leaf vegetation around the globe. The normalized difference vegetation index (NDVI), calculated using the near infrared and red reflectance bands, is frequently used to monitor vegetation growth cycles and health (Tucker et al. 1979; Myneni et al. 1997; Cleland et al. 2007). While NDVI is the most commonly used index, it is sensitive to external factors not related to the canopy itself, including leaf water content, atmospheric scattering, and snow. More recent studies focused on the analysis of land surface phenology have begun to include reflectance values from other portions of the visible and infrared portions of the spectrum, including the blue, shortwave infrared, and middle infrared bands to account for the interaction between snow and vegetation green-up (Delbart

et al. 2005). Delbart et al. (2005) argue that the use of NDVI in boreal regions suffers from uncertainty in predicting start of season (SOS) due to confounding effects of snow melt and suggests the use of the normalized difference water index (NDWI) to reduce these uncertainties. If a VI derived from satellite observations is to be used to monitor the duration of vegetation activity, it is desirable to compare the satellite retrieved phenological estimates with data observed at ground level. However, a principal disadvantage of phenological observation by satellite imagery is the complexity of validation of the data by ground observations that usually measure something quite different (Schwartz et al. 2002; Fisher et al. 2006). As a result, it is often unclear what the LSP metrics actually track. Since the relationship between satellite measures of LSP and phenological events of particular species or life forms is ambiguous, a diversity of satellite measures and methods has arisen.

Here we compare two start of season metrics based on NDVI and NDII for characterizing the land surface phenology of mountainous regions. Due to the rough terrain, harsh climate, and remoteness of many mountainous areas, few field observations exist to supply ground referenced values. This lack of ground observations is especially true at higher latitudes (Pepin and Losleben 2002; Fagre et al. 2003). However, previous

studies have found that topographic variables play a key role in modeling environmental processes such as snowmelt and accumulation; vegetation spatial patterns and life cycles; and available energy through solar radiation (Hopkins 1920; Burke *et al.* 2004; Geddes *et al.* 2005). Here we analyzed and compared the relationships between start of season and physical variables including elevation, aspect, and slope. We compared the results with Hopkins' bioclimatic law which states that start of season (SOS) is delayed, 3.3 days for every 100m increase in elevation, 4 days for every one degree change in latitude northward, 1.25 days for every one degree change in longitude westward.

3.2 Study Area

The study area consists of six geographic zones dispersed throughout the central and northern Rocky Mountains of both the United States and Canada (Figure 3.1) spanning a latitudinal range between 30°18'27N and 54°18'42N. Three of the six zones encompass the interior and boundaries of national parks while the remaining three are located within national forests or ecological research stations. These zones were chosen for their proximity both near and far from one another, and topographic complexity which results in a wide variety of temperature and precipitation values, as well as varied slope, aspect, and insolation effects. Elevations throughout our study

zones range between 697m to 4,195m. The terrain is rugged and rapid changes in elevation are common throughout all sites except Yellowstone National Park where variations in elevation are less drastic. Study zones are described from North to South below.

3.2.2 Jasper National Park (JNP)

JNP is the largest of the parks in the Canadian Rockies and spans over 10,878 km² beginning at 53°28'29N and ending at 52°8'10N. The three dominant vegetation zones are dry forested montane, subalpine, coniferous forest, and rocky tundra. Average elevation throughout the park is 2,332m with the highest mountain peak at 3,684m. Average yearly temperature is 1.94°C, average precipitation is 33.3cm.

3.2.3 Glacier National Park (GNP)

GNP is located at approximately 49°N with an elevation gradient extending from 800m to over 3000m. The park spans an area of 4,058km² and is split by the Continental Divide. The west side of the Park is influenced by cool moist Pacific maritime weather whereas east of the Continental Divide weather conditions are driven more by dry windy continental air masses arriving from the Canadian provinces. Dominant vegetation zones are coniferous forested valleys on mountain slopes, and

alpine tundra. GNP receives an average rainfall of 28.1cm and an average temperature of 5.3°C.

3.2.4 Lower Lewis Range (LLR)

The LLR begins just south of Glacier National Park and covers approximately 12,226 km² between 48°15'55N and 47°8'58N. Like GNP this area is split by the continental divide and experiences an average elevation of 814m with the highest point being 1,685m. An average temperature of 5.8°C and average precipitation of 27.1cm supports grasslands, shrublands, evergreen forest, and alpine tundra.

3.2.5 Bitterroot Range (BR)

This range is located in the panhandle of Idaho and westernmost Montana and is dominated by grassland and shrublands, montane forest, and alpine tundra. The study zone encompasses an area of 3,486 km² beginning at 46°38'55N and running south to 45°51'39N. Average yearly temperature is 5.7°C and average precipitation is 29.3cm. BR is divided into two areas including the northern Bitterroot and central Bitterroot with a maximum elevation of 3093m range.

3.2.6 Yellowstone National Park (YNP)

YNP is the core of the Greater Yellowstone Ecosystem and covers 8,987 km², mostly in the northwest corner of Wyoming beginning at 45°N. Sub-zero temperatures over-night are common and the average rainfall is 39.12cm per year, however it is not uncommon for higher elevations to get twice that amount. Elevation changes are less drastic in this zone, however the average elevation is higher than other sites at 2,524m with a maximum elevation of 4,195m. Dominant vegetation zones throughout the park are grass and sagebrush valleys, montane coniferous forest, and alpine tundra.

3.2.7 Niwot Ridge Long Term Ecological Research Station (NR)

The Niwot Ridge Long Term Ecological Research Station covers an area of 3,397 km², has an average elevation of 2,903m, and is home to extensive alpine tundra, montane forest, subalpine forest, and open meadow. NR and the surrounding area within the study zone (40°22'41N-39°44'8N) is characterized by an average temperature of 6.6°C throughout the year, increased solar radiation, and higher annual precipitation than the other study zones at 41.9cm.

3.3 Datasets and Processing

3.3.1 MODIS data

Two MODIS/Terra data products were used for this study. The MODIS/Terra Vegetation Indices 16-Day level 3 Global 1km spectral data (MOD13A2) for ISIN tiles h9 v04, h9 v05, h10 v03, and h10 v04 were gathered for the dates between January 1st 2007 and December 2007 a total of 23 scenes per year. The MOD13A2 exists of 13 layers including the blue, red, and near-infrared reflectances as well as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI). Both of these products allow for the observance of vegetation dynamics and health based on levels of chlorophyll in the foliage. Since chlorophyll absorbs red radiation and reflects near infrared radiation a decrease in values for the red reflectance occurs as the amount of green increases (Tucker 1979; Huete 1994; Huete et al. 2002). NDVI is based on the NIR (bands 2 centered at 858nm) and red reflectances (band 1 centered at 645nm) as follows:

$$NDVI = \frac{Band2 - Band1}{Band2 + Band1}$$

We used the binary MODIS quality flags to select only cloud-free data of ideal quality. The composites for each tile were stacked to create a time series spanning 2007. Each stacked tile was then re-projected into

Geographic Lat/Lon and mosaiked based on the georeferenced location to create one continuous scene between latitude 30°18'27N and 54°18'42N and longitude 99°49'31W and 120°2'40W (Figure 3.1).

Second we evaluated the MODIS/ Terra Nadir BRDF Adjusted Reflectance 16-Day level 3 Global 500m spectral data (MCD43A4) for 2007-2008. The MCD43A4 product is created with the use of a bidirectional reflectance distribution function which models values so as to represent the scene from a nadir view (Lucht et al. 2000). The MCD43A4 product includes the first seven MODIS reflectance bands. We calculated the normalized difference infrared index (NDII) using bands 2 (NIR) and 7 (MIR) ({Hardisky, 1983 #619}{Hunt, 1989 #618}) de Beurs and Townsend 2008) as follows:

$$NDII = \frac{Band2 - Band7}{Band2 + Band7}$$

The NDII data were projected to Geographic Lat/Lon and mosaiked to match the scene produced with the NDVI output.

3.3.2 SNOTEL data

SNOTEL daily historical average temperature data was obtained by state for 80 sites in Montana, 81 sites in Idaho, 80 sites in Wyoming, and 86 sites in Colorado (Figure 3.1) for the months of March-July 2007 (United

States Department of Agriculture, National Resources Conservation Service (<http://www.wcc.nrcs.usda.gov/snotel/>). SNOTEL data does not exist for the area study in Jasper National Park, (Canada).

Since site locations were limited within the individual study zones, we chose to examine all stations within each state. This allowed for a complete visualization and analysis of temperature related phenological patterns present. Minimum and maximum daily historic temperatures for each station where satellite data was also available were recorded. Average daily temperature was then calculated for each day at each station. Monthly averages for March, April, May, June and July at each station were derived by taking the mean of this result. In order to examine any potential latitudinal variations in temperature and SOS, each state was analyzed individually.

3.3.3 Digital Elevation Model

In order to examine the relationship of topographic variables with the timing of green-up in mountain vegetation three elevation datasets were acquired. The first two elevation models were obtained from the USGS National Map Seamless server (<http://seamless.usgs.gov/index.php>). The first dataset, the National Elevation Dataset (NED), was gathered for nine tiles including NED_21171976, 58168785, 64973515, 70644336,

10096502, 34161066, 58950525, 6590004, 99015392 at a 30m (1" second) spatial scale and is projected in NAD 1983. As this dataset only covers the contiguous U.S. an additional Shuttle Radar Topography Mission (SRTM) DEM was obtained at a spatial scale of 90m (3" second) for Jasper National Park which is located in southwestern Canada. To calculate aspect at a spatial scale corresponding to the NDVI data, a USGS Digital Elevation Model was obtained from Earth Resources Observation and Science (EROS). The two tiles utilized for our specific study area were W140N90 and W140N40. This GTOPO product has a spatial scale of 1km (30" second) and is projected in geographic WGS84.

3.4 Methodology

3.4.1 ArcGIS Derived Variable Creation and Analysis (Slope, Solar radiation, and Aspect)

Each of the digital elevation models consisted of a regular matrix of elevation values from which altitude functions including slope, aspect and solar insolation were calculated within a GIS and rendered for both visualization and analysis. Slope and solar insolation were created using the 30m and 90m NED, while aspect was calculated based on the 1km DEM. Each function's output was produced as an individual layer of values and was joined with the output for SOS as discussed below.

Slope and aspect were calculated using the ArcGIS Surface tool within the Spatial Analyst Toolset. Within the GIS, slope identifies the rate of maximum change in altitude, from each cell. The output slope values are in degrees from 0° to 90°. Aspect identifies the downslope direction of the maximum change in altitude from each pixel to its neighbors. The output values were expressed in positive degrees from 0 to 359.9, and were measured clockwise from north.

To derive insolation we used the solar radiation tool within the ArcGIS surface analysis toolset (Rich et al. 1994). The solar radiation was calculated based on the area insolation across each study zone. Calculations were performed for the entire year of 2007 at monthly intervals.

3.4.2 Land Surface Phenology Analysis

Several methods have been developed to detect the onset of green-up from vegetation index data (Reed et al. 1994; White et al. 1997; Zhang et al. 2003). While selecting the most appropriate method is difficult without additional ecosystem information, comparative studies have shown that thresholds based on variations of an $NDVI_{ratio}$ consistently estimate SOS dates that corroborate ground-based phenology data (White et al. 1997; White et al. 2009). For this analysis we used a threshold method based on an $NDVI_{ratio}$ of fifty percent (White et al. 1997). Here SOS is assumed to

have occurred on the date that the $NDVI_{ratio}$ rises past this designated threshold (Figure 3.2). This method was applied to every pixel in all six study zones.

Though NDVI is the most commonly used index, it is sensitive to external factors including leaf water content and snow. Both the middle infrared (MIR) and short-wave infrared regions of the electromagnetic spectrum have been used to measure leaf and canopy water content. The sensitivity of the MIR channel to water has led to the creation of several vegetation indices capable of responding to levels of water in vegetation (Hardisky et al. 1983; Hunt and Rock 1989). Delbart et al. (2006) explored the use of the normalized different water index (NDWI) developed from the SPOT-VGT 10 sensor data as the difference between NIR (0.78-0.89nm) reflectance and SWIR (1.58-1.75nm) reflectance to help eliminate the confounding effects of snow melt on the NDVI signal in boreal regions. Delbart et al. (2006) argue that the use of NDVI in boreal regions suffers from uncertainty based upon the fact that NDVI increases not only with green-up, but also during snowmelt. This premature increase in NDVI may lead to a misrepresented value for SOS that appears to be much earlier than the actual ground based observations. With the addition of the middle infrared (MIR) band of the MODIS sensor, any potential effects on the

estimations of SOS due to snowmelt should be controlled. This will be seen as a decrease in NDII values as snow melts and increase in values as vegetation begins to green-up (Figure 3.3) (Delbart et al. 2005). To assess this increase and calculate SOS, statistics of NDII increase following the minimum NDII are analyzed. In situations where vegetation green-up may occur during snowmelt the NDII decrease can mask the increase due to green-up. This will lead to a derived SOS value later than the actual SOS. In order to avoid any complications from this coinciding timing, the algorithm used retains the later of the two observations, which is 20% less than the minimum NDII increase (Figure 3.3). The following formula represents this:

$$T_{\text{greening}} = \max(t \in [0, 200] | (NDII(t) < NDII_{\text{min}} + \epsilon))$$

Here ϵ is chosen as follows: 1) it must be larger than the noise affecting the NDII time profile, and 2) it must be smaller than the first NDII increase due to vegetation growth. In addition, we insert a value of 200 as we assume that SOS will be prior to this day (July 18th) (Delbart et al. 2005).

In order to characterize the land surface phenology of all six study regions, start of season dates were calculated using NDVI. For two of these regions, LLR and YNP, start of season dates were also calculated using the above algorithm applied to NDII data.

3.4.3 Regression Analysis

To relate SOS to the physical parameters present within all six of our study zones the SOS output layer was overlaid with the DEM and the GIS derived outputs for slope and solar radiation. Ten percent of pixels within each study zone were randomly sampled. In addition to the above variables, longitude, latitude, and elevation were also extracted for each randomly selected pixel. A backward stepwise linear regression model was used to determine the independent variables with the highest coefficients of determination. Based on the following equation the model predicted SOS for each pixel:

$$\text{SOS} = \text{intercept} + \alpha\text{elevation} + \beta\text{Latitude} + \gamma\text{Longitude} + \delta\text{slope} + \zeta\text{solar radiation}$$

In the next step, we used a backward stepwise linear regression to examine predicted and derived SOS for four aspects; north, south, east, west. North facing slopes were designated as any aspect value falling between 315 and 45, Easterly slopes were 45 and 135, Southerly slopes were 135 and 225, and Westerly slopes were 225 and 315. This analysis was performed for the entire western mountain range.

In the final step, SNOTEL temperature data was included to examine the relationship between temperature and SOS. The model included monthly average temperatures for March, April, May, June, and July, elevation, slope, longitude, latitude, and solar radiation.

3.5 Results

3.5.1 Individual Study Zone SOS

Table 3.1 shows the relationship between the satellite derived SOS from NDVI and physical parameters present within mountainous regions including elevation, slope and solar radiation. Table 3.1 also shows the relationship of SOS with spatial locations of longitude and latitude for our six study zones. Results indicate that SOS can be determined for all zones independently with a significant coefficient of determination (R^2 -values between 0.55 and 0.64) (Figure 3.4). The best fitting model, with a R^2 of 0.64, was found in NR, the study area farthest south. NR is also the smallest study area with a sample size of only 326 points. Despite the southerly location of this site, the average elevation is consistently higher than at other more northerly locations and thus there are SOS dates later than LLR, BR, and YNP. JNP, the most northern of the six study areas, has the latest SOS dates. LLR had the lowest R^2 at 0.55. In addition, the model appears to under estimate SOS values in LLR, BR, and YNP before the 25th of April

but works well predicting later SOS values. The relationship between elevation and SOS within all six study areas was consistent with observed trends recorded in eastern deciduous forests by Hopkins in 1920 (Hopkins 1920). The range of SOS delay for every 100m increase in elevation is 3.9 days in JNP to 7.0 days in BR. Patterns found between SOS and longitude or latitude did not correlate to findings made by Hopkins.

Table 3.3 shows the relationship between satellite derived SOS from NDII (Figure 3.7) and variables including longitude, latitude, solar radiation, elevation, and slope. Significant relationships can be seen between SOS, elevation, longitude, and latitude for both LLR and YNP. Additional parameters including slope and solar radiation were minimally significant only for LLR but omitted from Table 3.3. The relationship between elevation and SOS follows closely with Hopkins' Law showing a delay of approximately five days for every 100m increase in elevation. The pattern shown for both longitude and latitude does not follow as closely with the findings of Hopkins as delays are 21 days for LLR and 18 days for YNP as longitude changes one degree westward, and SOS is delayed 10 days for every one degree change in latitude northward in LLR and 12 days for every degree change southward in YNP. For both LLR and YNP the

use of NDII appeared to work well for lower SOS but overestimated values when predicting higher SOS.

3.5.2 Western Mountain Range SOS

Results (Table 3.1) show that SOS dates can be predicted for the entire western mountain range with a significant R^2 of 0.58 (Figure 3.5). Here we found that SOS is delayed 4.6 days for every 100m increase in elevation. This result follows closely with Hopkins' Bioclimatic Law which states that there is an expected delay in SOS of 3.3 days for every 100m increase in elevation. While longitude was not significant, changes in latitude were determined to be a strong factor in SOS and indicated a 5.8 day delay for every one degree change in latitude northward. This result also followed closely with Hopkins' Bioclimatic Law (a one degree change in latitude northward will result in a delay in SOS of four days). Examined at this scale, slope and solar radiation were not highly correlated to SOS.

Results (Table 3.2) from additional analysis performed for the entire western mountain range based on aspect directions of north, south, east, and west, indicate that when examined by slope direction, the significance of SOS predictions, as related by the R^2 values, ranges between 0.35 and 0.51 (Figure 3.6). Here we found that for every 100m increase in elevation on a

northerly slope, SOS is delayed 5.2 days. For this same shift in elevation on a westerly slope, SOS is delayed 5.5 days. However, when elevation increases 100m on both the east and south facing slopes we find that SOS is delayed 6 and 6.1 days. At this scale Latitude is significant for all zones and a one degree shift northward delays SOS between 4.3 days to 6.5 days. Longitude is significant for all slopes except the north faces and delays SOS between 5.1 days to 7.1 days for every shift in one degree westward.

3.5.5 State-Wide Analysis at SNOTEL Locations

Parameter estimates from the backward stepwise linear regression (Table 3.3) show that SOS is strongly affected by change in elevation for Montana, Idaho, Wyoming, and Colorado. Delays in SOS based on elevation are similar to those seen in the NDVI and NDII analysis. The relationship with latitude indicates that SOS can be delayed as little as 3.2 days for Colorado, to as much as 8.5 days in Montana for every degree north. Monthly average temperature is a significant factor in determining SOS in Montana, Idaho, and Wyoming, however the months that provide the most significant input between all three states vary. Idaho exhibits SOS dates as early as March 21st and no later than May 25th and as seen in Table 3, the most significant correlation with temperature appears to be in April where an increase of one degree Celsius leads to an earlier SOS of 10.30

days. Inversely, an increase of one degree Celsius in March delays SOS by 8.66 days. Montana, with SOS dates ranging from April 1st through June 3rd, shows the strongest relationship with June where an increase in monthly average temperature of one degree Celsius initiates SOS 16.95 days earlier, while the same increase in average temperature in May will delay SOS 16.94 days. SOS dates throughout Wyoming show the strongest association with average temperatures in May with an advance in SOS of 6.4 days for every degree Celsius increase. An increase of one degree Celsius in April prolongs the dormant phase with 6.31 days. Wyoming's SOS dates range from April 9th to May 27th. SOS dates in Colorado showed no direct relationship to average monthly temperature.

3.6 Discussion

3.6.1 The Use of NDVI and NDII for Determining SOS

Characterizing land surface phenology in mountainous environments is hindered by the varying topography, shadowing, and lack of ground based observations for validation. With the use of data collected via satellite sensors, vegetation indices can be produced that allow for the monitoring and characterizing of vegetation phenology patterns in these remote areas. Both NDVI and NDII data can be used to predict SOS with a significant R^2

for each study zone despite the variability present in land cover, elevation shifts, and general topographic characteristics. While NDVI works best for predicting later SOS values which are likely to be at higher elevations, NDII is more useful when predicting earlier SOS which we assume to be associated with pixels sampled at lower elevations. The pattern seen in the overestimations of SOS are not unexpected assuming snowmelt is the primary cause for the early estimations present. The use of an $NDVI_{ratio}$ with a threshold value of 50 percent can be helpful in limiting the affect of snowmelt on NDVI derived SOS estimations as the NDVI value must have reached half of its' yearly maximum to assign SOS. However this did not account for all instances where the increase of NDVI due to snowmelt prevented the observation of actual green-up. It remains unclear why the results from this particular research do not fully confirm findings by Delbart et al. (2005 and 2006) which expressed the benefits of using the SWIR or MIR band in the creation of spectral indices used to monitor spring phenology. Delbart et al. found that NDWI, which is comparable to NDII, was more efficient in estimating the date of onset of greening than other methods based on NDVI in the context of boreal regions. As NDII is more sensitive to water content and relates SOS to the increase in the NDII signal after the initial decrease due to snowmelt, it is possible that this method

over compensates, delaying the observation of vegetation green-up at higher elevations which experience snow cover much later in the year. It has been shown that green-up may occur either during or after snowmelt (Delbart et al. 2005). If a coinciding of these events occurs, the NDII increase due to green-up may be masked by the decrease which is simultaneously occurring during snowmelt. At lower elevations, snowmelt is more likely to occur earlier which allows stability to remain in the NDII signal leading to a more reasonable assessment of SOS.

3.6.2 SOS throughout our study region

The relationship between temperature and vegetation phenology is of increased importance as researchers continue to analyze the biotic implications of responses to climate change (Schwartz et al. 2006; Khanduri et al. 2008). It is of particular interest in high elevation and high latitude environments due to recorded recent warming trends and anticipated continued warming of these regions (Kramer et al. 2000; Myneni et al. 1997). Temperature however is not the only driving factor of vegetation phenological shifts including spring green-up. SOS in vegetation is controlled by numerous forces including but not limited to elevation, longitude, latitude, slope, aspect, and solar radiation (Hopkins 1920; Burke et al. 2004; Geddes et al. 2005). In mountain environments these factors can

vary greatly between short distances which contribute to very specific patterns and processes among the plants present (Pepin and Losleben 2002). These variables can be used as biophysical proxies to predict SOS. We used a linear regression to relate elevation, longitude, latitude, slope, and solar radiation with SOS for six individual study zones along the central and northern Rocky Mountains. When examining the zones independent of one another we found that elevation was consistently the most significant variable and was highly correlated to SOS as derived from both NDVI and NDII data. This result corresponds to findings from Hopkins (1920) which stated that elevational changes proved to be the most significant determinant in seasonal variations within vegetation. In addition, the pattern seen with elevation at all study zones follows closely with Hopkins' findings in the eastern U.S. which asserts that for every 100m increase in elevation a 3.3 day delay in SOS of 3.3 days will occur. This pattern was also found when the results were examined at a regional scale (the entire range of study zones) and a state-wide scale including temperature measurements.

The aspect of a slope can have very significant impacts on vegetation type, soil type, snowmelt, insolation, runoff, and fire patterns, which may all lead to variations in phenological patterns observed within aspects of

varying degrees (Bliss 1956; Mark 1970; Ratcliffe and Turkington 1989). In the northern hemisphere, south facing slopes receive more direct sun and are subsequently drier while north facing slopes experience lower levels of evapotranspiration due to decreased sunlight and cooler winds which lead to microclimates that experience increased snow accumulation and later snowmelt (Barry 1992; Walsh 2004; Wagner and Reichegger 1997). When we incorporated aspect into the analysis at the regional scale, changes in elevation remain the primary driver of SOS (Table 3.2). We also find that both longitude and latitude are important variables in delaying or advancing SOS estimates.

When examined along with temperature, elevation remained the most significant predictor raising the R^2 values as much as 0.31 points when included in the regression, however, even with the inclusion of elevation, significant relationships were found between SOS and monthly average temperatures. For Montana, Idaho, and Wyoming results indicated that an increase of one degree Celsius would advance start of season anywhere from 16.95 days (Montana) to 6.4 days (Wyoming), confirming observations in the existing research that higher temperatures speed plant development and contribute not only to an earlier onset of spring, but also to a lengthened growing season (Penuelas and Filella 2001; Menze and

Fabian 1999; Myneni et al. 1997). An additional explanation of earlier SOS estimations present within our results relates to varying vegetation classes among samples. As temperature shifts, vegetation types shift in tandem. Seasonal green-up patterns will vary dependent on these vegetation classes, some experiencing much earlier SOS than others. In contrast, when temperatures increase in the months that precede SOS spring can be delayed up to 9 days as observed throughout Idaho and Wyoming. We suggest that this pattern is attributed to an underlying hypothesis found in the literature (Cannel and Smith 1986; Meehl 2000; Gu et al. 2008) regarding the deleterious effect of late frost events on premature vegetation growth induced by mild winter temperatures and warm early springs, brought on by a warming climate. The initial loss of vegetation development can delay the recorded SOS in both ground and satellite observations as plants strive to regain stamina in their physiological processes (Schwartz 1998; Gu et al. 2007). The lack of correlation found in Colorado among SOS and temperature may be attributed to the uniformly high elevational range of SNOTEL locations. In Colorado, the average elevation is 3,126m which is significantly higher than that found in Montana (2126m), Idaho (1992m), and Wyoming (2643m). With minor elevational variation, temperature remains relatively constant resulting in negligible impact on SOS.

Results for the relationship between SOS, as derived from NDVI data, and latitude and longitude did not correlate with Hopkins' findings when examined for each separate study zone. We anticipate this was due to the negligible change ($\leq .93^\circ$ of latitude and $\leq 2.81^\circ$ of longitude) in both variables and the large spatial resolution of our pixels. When examined in relation to SOS as derived from NDII these variables displayed results that were more similar to what would have been expected assuming that Hopkins' findings translate across the entire United States. This may be attributed to the smaller spatial resolution of the NDII data which allowed for a study of four times the number of samples within the same area. At the regional scale latitude did respond as would have been predicted following the bioclimatic law. For this analysis the latitudinal range was $53^\circ 28' 29\text{N}$ and $39^\circ 44' 8$, a much larger change than the individual zones experience.

3.7 Conclusion

Mountain environments present unique challenges to the characterization of vegetation phenology, because they represent continuous changes in elevation, temperature, slope, aspect, and solar radiation. Observations derived from data collected onboard space born satellite sensors provide excellent opportunities to characterize the land surface phenology of remote environments worldwide (White et al. 1997;

Zhang et al. 2004; Delbart et al. 2005; White et al. 2009). Here we compare the SOS estimates based on NDVI, the most commonly used index in studies examining vegetation dynamics and phenology, and NDII, another spectral index which has recently been used to reduce the effects of snowmelt on the estimation of SOS. The results of our analysis indicate that both NDVI and NDII can be used with varying degrees of confidence to predict SOS in the North American western mountain range. However, in future studies we aim to develop methodology combines properties of both indices. This combination will allow for a more accurate estimation of SOS values in boreal regions which experience large amounts of snowfall and subsequent snowmelt.

Future analysis of mountain phenology is needed to enhance our current understanding of the effects that elevation, slope, aspect, and solar radiation have on SOS. Here we found that the seasonal green-up pattern of the western mountain range closely follows the relationship between elevation (at both the local and regional scale) whether aspect is accounted for or not, and latitude with start of season as stated by Hopkins Bioclimatic Law (Hopkins 1920). However, the pattern that Hopkins found in relation to latitude and longitude are shown to not be applicable when examined at the local scale alone. Though very little significance was found at this scale

in relation to slope, and solar radiation, it has been shown that these factors can strongly affect vegetation characteristics including phenology (Malingreau 1986; Moulin et al. 1997; Schwartz and Reiter 2000). With the use of finer resolution satellite data it may be possible to ascertain patterns and trends not revealed at a resolution of 1km. The new Web-Enabled Landsat Data (WELD) project fuses the Landsat Thematic Mapper data with MODIS land products to systematically generate a seamless mosaic dataset at monthly, seasonal, and annual temporal resolutions (Roy et al. 2009). The resulting output is a high spatial resolution product (30m), with 14 bands which can be used to create numerous spectral indices for vegetation phenology studies. The availability of such a dataset provides an opportunity to study patterns and processes at a higher spatial resolution which may allow a representation of the relationships between variables that are influenced by minor changes in spatial location but strongly contribute to processes in vegetation dynamics.

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Figures and Tables

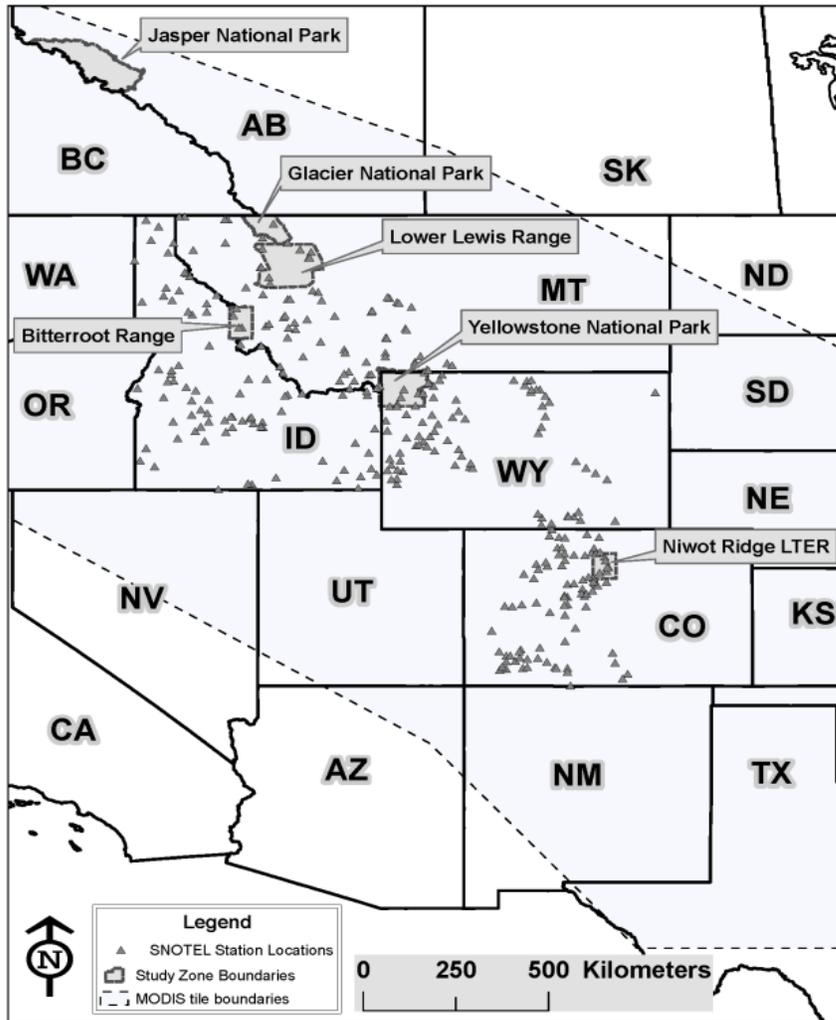


Figure 3.1 Map of the western United States and southwestern Canada showing the six study zones. These sites span a range of latitudes from 53°28'29N to 39°44'8N; elevations of 897m to 3971m, and slopes as little as 0° to as steep as 88.32°. SNOTEL sites analyzed are indicated by the grey triangles. The full mosaiked MODIS boundary is designated by the light grey dashed line.

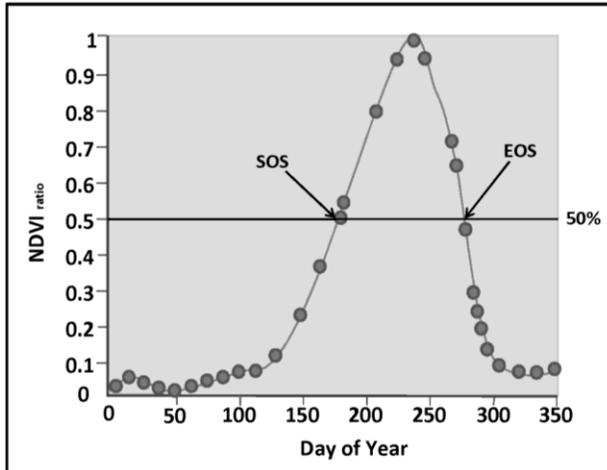


Figure 3.2 This graph represents a NDVI signal for an entire year. Start of season (SOS) is estimated as the point at which the NDVI signal surpassed 50% of its total range. End of season (EOS) is estimated as the point when NDVI drops back passed the 50% mark.

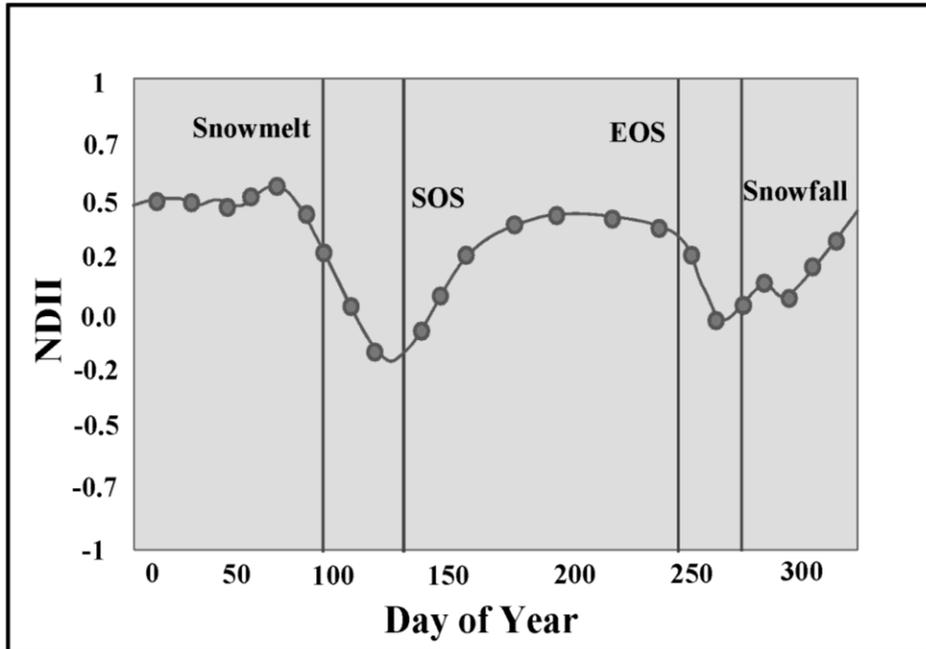


Figure 3.3 This graph represents a time evolution of NDII for an entire year. NDII values are highest when snow is on the ground and begin to decrease as snowmelt occurs. SOS is estimated as the date that the NDII signal begins to increase again and EOS estimated as the date that the NDII signal begins to decrease.

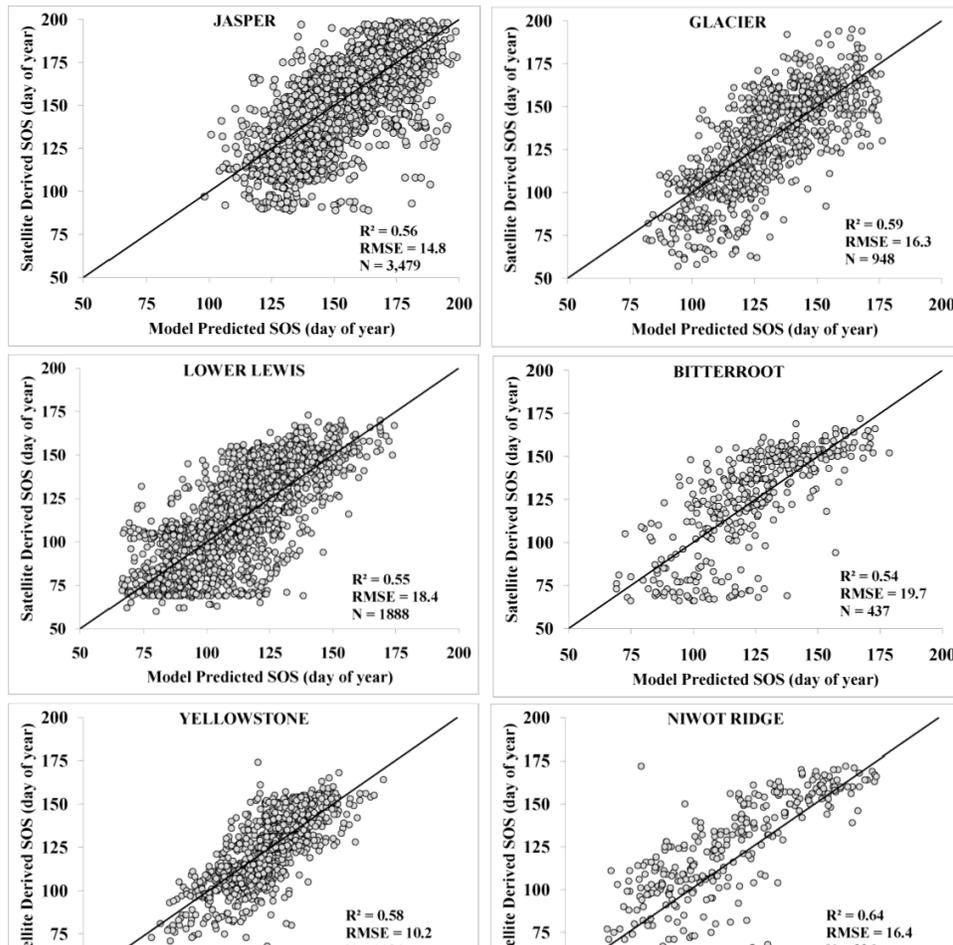


Figure 3.4. Predicted SOS date based on significant variables, against actual SOS as determined using the $NDVI_{ratio}$ method. Study Zones run north to south. The SOS can be predicted for all the zones with a significant R^2 .

Figure 3.4. Predicted SOS date based on significant variables, against actual SOS as determined using the $NDVI_{ratio}$ method. Study Zones run north to south. The SOS can be predicted for all the zones with a significant R^2 .

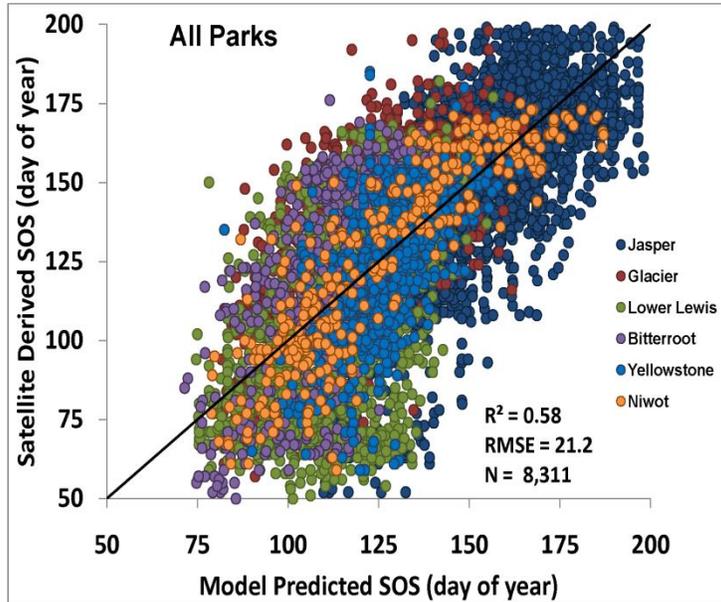


Figure 3.5 Results derived from a linear regression model for the entire western mountain range. While SOS can be predicted for the entire western mountain range with a significant R^2 , when examined together an obvious pattern of under prediction within the model is observed for the earlier SOS values.

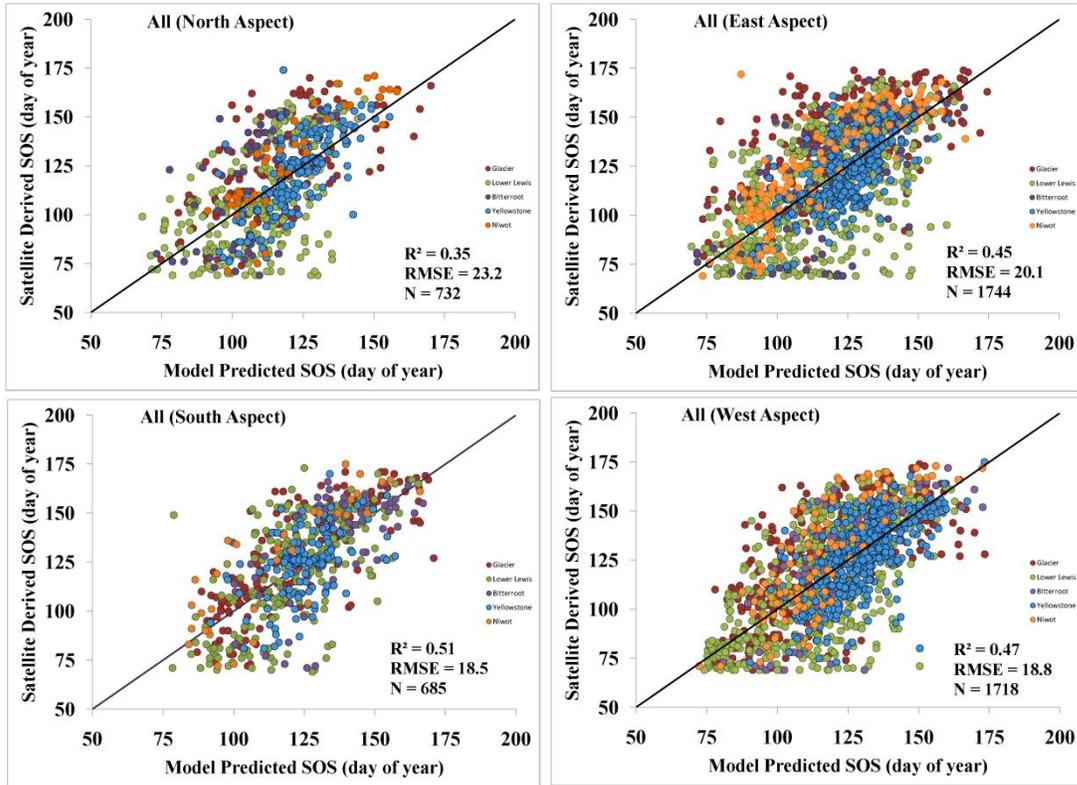


Figure 3.6 Results derived from a linear regression model for the entire western mountain range based on aspect categories of North, South, East, and West. SOS values were determined using the $NDVI_{ratio}$ method and can be predicted for each aspect, however the strength of the prediction varies across direction. Here we see that the model under predicted earlier SOS values. This under prediction is similar to the results for all produced from the SOS analysis not characterized by aspect.

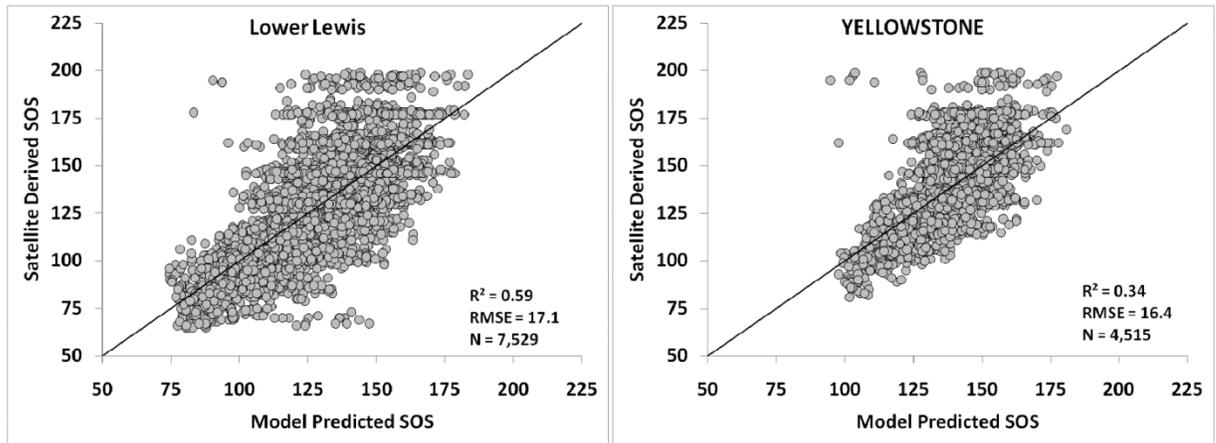


Figure 3.7 Predicted SOS date for Lower Lewis Range and Yellowstone National Park based on significant variables, against actual SOS as determined using NDII data. For both LLR and YNP SOS estimates appear to be over predicted at higher elevations.

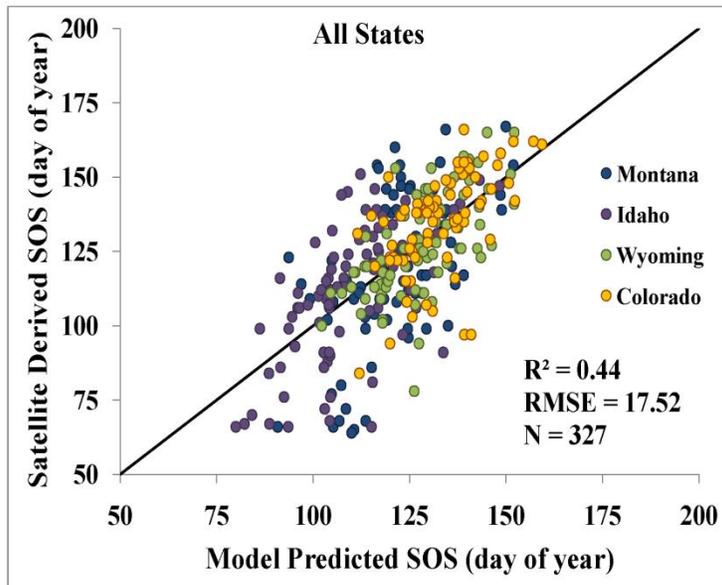


Figure 3.8 Results derived from a linear regression model for all four states at the SNOTEL locations. The model tends to under predict SOS at lower elevations, most significantly for Montana.

Table 3.1 Indicates parameter estimates for each significant independent variable as it relates to SOS within the specified study zone. Negative longitudinal values indicate a delay in SOS westward while negative latitudinal values indicate a delay in SOS southward. In addition to the parameters below, slope was significant for JNP. The amount of solar radiation present did significantly influence SOS predictions for GNP during the months of March, May, and July; LLR for the month of February only; and BR for both February and March. SOS in YNP and NR showed no significance to solar radiation or slope. Missing estimates are not significant.

| | JNP | GNP | LLR | BR | YNP | NR | All Zones |
|----------------------|----------------|---------------|-----------------|-----------------|----------------|-----------------|--------------|
| Elevation | 0.039 | 0.043 | 0.054 | 0.070 | 0.055 | 0.059 | 0.046 |
| Longitude | -271.63 | N/A | -1371.01 | -1639.10 | N/A | N/A | N/A |
| Latitude | -301.28 | 243.12 | 345.68 | 328.55 | -267.42 | -1012.15 | 5.88 |
| R² | 0.56 | 0.59 | 0.55 | 0.54 | 0.58 | 0.64 | 0.58 |

Table 3.2 Indicates parameter estimates for each significant independent variable as it relates to SOS and aspect direction. Negative longitudinal values indicate a delay in SOS westward while negative latitudinal values indicate a delay in SOS southward. The amount of solar radiation present did significantly influence SOS predictions for south facing slopes during the months of February, May, and June and for west facing slopes during the months of February and March Missing estimates are not significant.

| All Zones | North | East | South | West |
|----------------------|-------|-------|-------|-------|
| Elevation | 0.052 | 0.060 | 0.061 | 0.055 |
| Longitude | N/A | -5.14 | -7.09 | -5.71 |
| Latitude | 6.51 | 4.46 | 4.32 | 4.82 |
| R² | 0.35 | 0.45 | 0.51 | 0.47 |

Table 3.3 *Parameter estimates for each significant independent variable as it relates to SOS as determined from NDII data within two of the six study zones. SOS is delayed 21 days for every degree westward for LLR and 17 days for YNP. Based on these estimates, a change of one degree in latitude northward leads to a SOS date that is 10 days later in LLR, while the same change southward leads to a delay in SOS of 11 days in YNP. In addition to the above parameters, SOS is significantly influenced by slope and solar radiation for the months of February through July only within the LLR.*

| | LLR | YNP |
|----------------------|---------------|---------------|
| Elevation | 0.050 | 0.053 |
| Longitude | -21.31 | -17.98 |
| Latitude | 10.42 | -11.67 |
| R² | 0.59 | 0.34 |

Table 3.4 Parameter estimates for the SNOTEL temperature analysis indicate that elevation, monthly average temperature, and latitude are strongly significant determinants of SOS at SNOTEL locations in all four states. Based on estimates for elevation, SOS is delayed as little as 3 days in Colorado for every 100m increase in elevation to as much as 60 days in Montana. Neither slope nor solar radiation significantly influences SOS.

| | Montana | Idaho | Wyoming | Colorado | All Zones |
|----------------------|---------|--------|---------|----------|-----------|
| March | N/A | 8.66 | N/A | N/A | 1.39 |
| April | N/A | -10.30 | 6.31 | N/A | N/A |
| May | 16.94 | N/A | -6.40 | N/A | -2.41 |
| June | -16.95 | N/A | N/A | N/A | N/A |
| Latitude | 8.55 | 4.17 | 4.95 | 3.28 | 3.18 |
| Elevation | 0.60 | 0.03 | 0.04 | 0.04 | 0.03 |
| R² | 0.48 | 0.43 | 0.47 | 0.31 | 0.44 |