Spatiotemporal Variability Of Plant Phenology In Drylands: A Case Study From The Northern Chihuahuan Desert

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SPATIOTEMPORAL VARIABILITY OF PLANT PHENOLOGY IN DRYLANDS: A CASE STUDY FROM THE NORTHERN CHIHUAHUAN DESERT

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Master’s Program in Environmental Science

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SPATIOTEMPORAL VARIABILITY OF PLANT PHENOLOGY IN DRYLANDS: A CASE STUDY
FROM THE NORTHERN CHIHUAHUAN DESERT

By

NAOMI ROBIN LUNA, B.Sc.

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
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of the Requirements
for the Degree of

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Acknowledgments

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Abstract

With global change, which includes climate change, there is a sense of urgency to understand how shifts in climate will affect ecosystems. Although several studies have improved understanding of how and why some ecosystems respond, most studies have not explored simultaneous responses of different land cover types throughout a given region. Dryland ecosystems, such as the Chihuahuan Desert, appear to respond to climate variability and currently make up about 40% of global land surface area. It is expected that drylands will expand to cover 60% of land surface area on earth by mid-century making this ecosystem more critical to global land-atmosphere interactions than previously thought.

The goal of the proposed study is to determine how plant phenology in multiple desert land cover types responds to seasonal and inter annual climate variability over five years. Phenology is the timing of major growth stages in plants and animals which has been shown to provide important insights into the environmental state heavily influenced by climate change. Dryland plant phenology is relatively understudied.

Time series imagery acquired by static digital cameras in five land cover types on the USDA Jornada Experimental Range in Southern New Mexico between 2010 and 2015 were analyzed with alternative remote sensing techniques at the landscape level phenology. At each site, both the phenology of the landscape and replicates of key species were analyzed using custom phenology analysis software developed within the Systems Ecology Lab at the University of Texas at El Paso. This study is expected to expand the current knowledge of the effects of climate variability and change in dryland ecosystems by understanding which land cover types
and species are more/less sensitive to change. The study is also novel in that it will explore
image processing methods that have yet to be fully explored by ecosystem scientists.

Grasses displayed greater seasonal fluctuation in greening thought to be tied closely to rainfall
events, where shrubs displayed a more consistent inter-annual growth pattern. This is
hypothesized to be attributed to accessibility to deeper water storage attainable by the more
extensive root systems commonly found in shrubs. Exploration into the use of alternate spectral
signatures from images to capture timing of key growth stages proved to be useful in the patchy
land cover. More extensive research needs to be done, but this study has hinted to advantages for
using alternate color models for processing images within these extreme and complex
ecosystems. These results may provide strong implications to predicting future ecosystem states
of the northern Chihuahuan Desert region including ecosystem properties and processes such as
biodiversity and land-atmosphere carbon fluxes.
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1. Introduction

1.1. Background and Rationale

1.1.1. Definition and importance of plant phenology

Phenology is the study of the timing of growth and reproductive patterns for a particular organism. For plants, this includes events such as the timing, rate of development, and duration of initial leaf growth, production of flower buds, opening of flowers, release of seeds, and onset of senescence. Plant phenology is sensitive to climate, and the alteration of a range of ecosystem properties and processes (Cook et al., 2012; Crimmins et al., 2010; Menzel et al., 2006; Zhang & Friedl, 2004). The study of plant phenology and phenological change has been undertaken for centuries, but the fervor for phenological studies has increased dramatically over the past few decades due in part to the urgency for understanding how climate change will impact plant phenology both within and between ecosystems (Ibáñez et al., 2010; Menzel et al., 2006; Richardson et al., 2009). As early as the eighteenth century, plant phenology had already been linked to climatic conditions. Such evidence suggests that climate change will likely alter spatial and temporal phenological patterns causing changes in ecosystem properties and processes (Bowers & Dimmitt, 1994; Huenneke et al., 2002; Joiner et al., 2014; Munson et al., 2013).

Research has linked shifts in spatial and temporal ecosystem properties and processes to changes in plant phenology (Cook et al., 2012; Joiner et al., 2014). Plant-animal interactions can be particularly sensitive to the timing and duration of specific plant growth stages (Bascompte et al., 2016; Elzinga et al., 2007; Hegland et al., 2009). In a study that examined plant-animal relationships for selected small rodent species in the Chihuahuan Desert, for example, a strong relationship between small mammal population size and the timing of plant growth development
was noted (Ernest et al., 2000). Similarly, the timing of plant production relies heavily on the timing and duration of climatic conditions, such as, precipitation and temperature which can shift due to climate change (Ernest et al., 2000).

There are various motivations and benefits for monitoring plant phenology both in managed (e.g. agriculture, grazing) and unmanaged settings (e.g. conservation, invasive species). Advancement of plant phenology research has been especially important in agriculture because research findings have helped to improve yield, the efficiency of agricultural production, and economic gain (Bowers & Dimmitt, 1994; Loomis & Connor, 1992). In most modern agricultural operations, the timing of phenophases such as flowering and fruiting provides insight to the likely timing and success of proceeding phenophases such as seed set, which can be used to predict the timing of harvests and the logistics of transportation of products to market (Ahrends et al., 2008; Campillo et al., 2008; Morisette et al., 2009).

Although agriculture might be a more obvious and relatable sector that relies on plant phenology studies, there are other sectors that rely on these studies/observations also. Japanese festivities, for example, celebrate the production of blossoms from the Japanese cherry trees which is of critical economic and social importance (Allen et al., 2014). It was determined that with increasing temperatures flowering of Japanese cherry trees might occur one month earlier by mid-century (Allen et al., 2014), which could mean having to adjust the timing of festivities to ensure festivities coincide with peak flowering. Furthermore, the economic profitability of honey production and the associated links to pollination success can be strongly dependent on the interaction, or lack of interaction between honeybees and flowering phenology (Bagella et al., 2013). More commonly, phenophases are used as a metric of ecosystem productivity where
shifts or differences in climate and other ecosystem properties and processes are recognized constraints and controls (Kramer et al., 2000).

Monitoring plant phenology has been used to show the impacts of climate change on plant species and ecosystem dynamics (Arora & Boer, 2005; Cleland et al., 2006; Richardson et al., 2007). Research in colder ecosystems provide evidence that decreasing snow depth and earlier snowmelt as a result of climate change has already had and will likely continue to play a significant role in plant responses (Cooper et al., 2011; Van Wijk et al., 2003; Wipf et al., 2009). The growing season for most areas in the Arctic and subarctic is limited to the summer months (May-August/September) (Euskirchen et al., 2006; Tucker et al., 2001). This short growing season is only exacerbated when the timing of snowmelt occurs later each successive year coupled with decreasing snow depth which makes it more difficult for plants to establish strong roots (Cooper et al., 2011; Van Wijk et al., 2003). “Green-up” of plants within a given ecosystem marks the beginning of a new growing season and ultimately controls other phenological stages (e.g. flowering, fruiting, seed set) both for individual plants and whole ecosystems (Cong et al., 2013; Pettorelli et al., 2005; Schwartz & Karl, 1990). Global studies have noted a variable but generally earlier onset of green-up across biomes, further providing evidence that climate change is impacting ecosystems (Badeck et al., 2004; Cook et al., 2012; Keenan et al., 2014; Peñuelas et al., 2009). Furthermore, certain plant species may succumb to critical thresholds that can threaten plant diversity and distribution. For some species, such thresholds could determine their listing on endangered species lists in the future (Kelly & Goulden, 2008; Thomas et al., 2004; Thuiller et al., 2005).
Capturing spatial and temporal canopy state patterns can give insight to energy, water, and land-atmosphere exchange of carbon within the ecosystem (Cleland et al., 2007; Geesing et al., 2000; Joiner et al., 2014; Kurc & Benton, 2010; Richardson et al., 2013). Carbon-cycling is closely linked to the timing of greening in most ecosystems (Joiner et al., 2014; Mizunuma et al., 2013). In drylands, phenology and C-cycling are strongly linked (Knapp et al., 2008; Kurc & Benton, 2010). Most modern studies reporting on such activities, have utilized the analysis of time-lapse photography from stationary digital cameras using digital image analysis techniques (Brown et al., 2016). As mentioned above, agricultural practices rely heavily on phenological observations and the analysis of digital imagery from stationary cameras has been shown to provide unbiased and non-subjective observations for determining more accurate harvest times (Ahrends et al., 2008; Campillo et al., 2008; Crimmins & Crimmins, 2008; Kurc & Benton, 2010; Przeszlowska et al., 2006; Richardson et al., 2007; Vanamburg et al., 2006). Other disciplines that have increasingly used static digital camera stations include, but are not limited to, wildlife/habitat monitoring (Bater et al., 2011; Brawata et al., 2013; Deacy et al., 2016), coastal erosion monitoring (Jones et al., 2009; Walker, 2014; Whitehead et al., 2010), and dust monitoring (Lorenz, 2009; Skiles et al., 2015). Several of these studies have demonstrated direct links to improved habitat management. Many different areas of study utilize time lapse images for data collection due to the ease by which high temporal resolution observations can be made, decreased field time, improved degree of quantifiable results, and generally higher quality data; all of which have stimulated the digital image revolution in the environmental sciences (Julitta et al., 2014; Keenan et al., 2014; Melaas et al., 2016; Nagai et al., 2014; Toomey et al., 2015; Young et al., 2015).
1.1.2. Biophysical controls and relationships of plant phenology

Abiotic factors beyond climate change can influence the phenological patterns of plants. Biophysical controls such as spatial distribution, light availability and strength, and soil moisture conditions and geographic variability can alter plant phenological patterns (Forrest et al., 2010; Parmesan & Yohe, 2003; Root et al., 2003; Rosenzweig et al., 2008). The magnitude of impact from any given controlling factor can depend on the stresses from multiple co-occurring biophysical factors including competition among other plant species for space, light, and water (Harris, 1977; Myneni & Williams, 1994; White et al., 1997). Light availability and light intensity vary with canopy structure (Cheng et al., 2006), which can also be influenced by atmospheric conditions (e.g. clouds, dust) (Kurc & Benton, 2010; Loomis & Connor, 1992; Rathcke & Lacey, 1985). Some plant species, including several perennial grasses in dryland ecosystems, grow under the canopy of shrubs, which can limit light availability for these grass species (Archibald & Scholes, 2007; Tucker et al., 2001; Van Auken, 2009) and lead to delayed growth (Archibald & Scholes, 2007; Thomson & Siddique, 1997). Soil moisture can also influence plant phenology by either accelerating or delaying plant growth when optimal conditions do not apply (Kidron & Gutschick, 2013; Kurc & Benton, 2010).

Plant phenology also influences the biological structure and function of ecosystems in multiple ways. These include but are not limited to: the timing of flower emergence that may directly affect key pollinator’s cycle (Chew & Whitford, 1992; Forrest et al., 2010; Lightfoot et al., 1989) grain production which is an important energy source for some small mammals (Brown, et al., 1979); roosting environments for various winged animals (Matuzak & Brightsmith, 2007; Ober et al., 2005; Scott, 2004); and nesting sites for various species that rely on specific plant
growth stages for rearing offspring (Hingrat et al., 2007; Sedinger & Raveling, 1986; Wagner, 1997). Litter fall is an important phenological stage that may control nutrient cycling (Barlow et al., 2007; Campanella & Bertiller, 2008; Facelli & Pickett, 1991). As the importance of plant phenology to organism and ecosystem structure and function has been increasingly recognized, a plethora of methodologies have developed to heighten the intricacies of phenological research and that has permitted scaling of studies across broader scales of space and time (Joiner et al., 2014; Moore et al., 2016; Nelson & Papuga, 2009; Piao et al., 2007).

1.1.3. Approaches to measuring plant phenology

Various methods exist to measure plant phenology, but some are more efficient and less cumbersome than others. Some of the more commonly practiced methods include (1) human observations, which require a researcher to physically go out to the field, monitor, and record plant phenological stages (phenophases). Although in-situ observations are still commonly practiced, (2) remote sensing techniques are not subjective, are less expensive, can generally cover a much larger area, and can record at higher frequency making this a highly preferred method in most modern phenological and multi-scale phenological studies. The analysis of satellite imagery has been used to monitor green-up and senescence at the landscape or regional scale for several decades (Archibald & Scholes, 2007; Cong et al., 2013; White & Nemani, 2006) and allows researchers to more easily interpret phenological change at regional or global scales (Allen et al., 2014).

Satellite imagery can be robust and expensive if high quality data is needed, but alternate remote sensing techniques exist that capture imagery over smaller areas at higher resolution (e.g. ground-level images), yet still permit insightful ecosystem studies (Browning et al., 2015; Ma et
While satellite imagery captures regional scale ecosystem productivity there are smaller scale techniques that are optimal for capturing landscape and plant level phenological trends. Hard-mounted digital cameras that capture repeat imagery of a fixed field of view (FOV) within RGB (red, green, and blue) color space (phenocams, Figure 1.1) have become popular and have arguably transformed phenological research over the past decade.

Phenocam images are made up of pixels that each contains a ratio of red, green, and blue channels (Barsky, n.d.; Connolly & Fliess, 1997; Saitoh et al., 2012; Sonnentag et al., 2012). The quality of such images depends on the capacity of the camera itself. The more pixels the camera can capture for each images, the more detail will be represented. The quality needed in a camera depends on the goals of the project. The specifications of the cameras used for this project will be addressed below. Digital time lapse photography and associated image analysis is now a popular data collection method that can be used to cheaply and consistently record plant phenological trends in most ecosystems (Ansley et al., 2001; Richardson et al., 2007). For plant phenological observations, a greenness index (derived from the RGB color model) within a given region of interest (ROI) in the image is typically what most researchers focus on (Benton et al., 2008; Hufkens et al., 2004; Toomey et al., 2015). This approach is generally sufficient to capture plant to landscape phenological change (Bater et al., 2011; Mizunuma et al., 2013; Toomey et al., 2015). There are, however, alternate color models that remain poorly explored in the ecosystem sciences that may be equally useful adept as the aforementioned RGB color model. In order to fully understand how each color model is represented and applied to image analysis techniques, the following section will expand on these concepts and their applications to phenological studies.
Figure 1.1: Tripod with a hard-mounted digital camera programmed to acquire repeat images of a fixed field of view (Image: Robin Luna).
RGB color model:

Figure 1.2: RGB color model. R=red channel, G=green channel, and B=blue channel (Barsky, n.d.).

RGB (red, green, blue) is an additive color model, which means the color perceived in an image depends on how many red, green, and blue rays are added to each pixel and collectively will represent the image being captured (Figure 1.2) (Connolly & Fliess, 1997). RGB closely matches the human perceptions of color (Connolly & Fliess, 1997; Ford & Roberts, 1998). RGB is the standard color model used for plant phenological analysis because of its adequacy in representing greenness within a given ROI (Bater et al., 2011; Proulx & Parrott, 2008) and is what affordable off-the-shelf cameras offer. An equation (Equation 1) is readily used that calculates this greenness within the image, which is critical for calculating the amount of green captured within a given ROI (Hufkens et al., 2004; Richardson et al., 2007; Vezhnevets, n.d.). This equation, coined the green excess index (GEI), calculates greenness in vegetation based on the absolute channel brightness (DN) for green with respect to red and blue channels for a given ROI (Bater et al., 2011; Graham et al., 2009; Mizunuma et al., 2013; Seager et al., 2007). Other commonly used equations derived from the RGB color model include the normalized difference
vegetation index (NDVI; Equation 2) (Gamon et al., 1995; Gamon et al., 2013; Richardson et al., 2007), and more recently, the green chromatic coordinate (GCC; Equation 3) (Ahrends et al., 2008; Klosterman et al., 2014; Sonnentag et al., 2012; Toomey et al., 2015). These color models have all been tested rigorously in different studies for overall efficacy and thus, have been adopted as a few of the more reliable indices for phenocam-based based plant phenological studies (Benton, 2009; Richardson et al., 2007; Toomey et al., 2015).

Richardson’s (etal.) 2007 paper provided the building blocks for future plant phenological studies, which included the use of the green excess index (GEI) as the basic equation rooted from the RGB color model that allows researchers to quantify the temporal “greenness” of a landscape and growth trends that can be linked to climate variability and change (Migliavacca et al., 2011; Mizunuma et al., 2013; Richardson et al., 2007, 2009). Along with GEI, the indices NDVI and GCC have proven to be both reliable and informative for documenting changes in green plant productivity in a given ecosystem (Gamon et al., 2013; Huemmrich et al., 2010; Migliavacca et al., 2011). Although RGB color space is regularly used in ecological research there are several important caveats; it is device dependent, there is a high correlation between color channels, and there is mixing of chrominance and luminance data, which can limit the use of this color model for some analyses (Vezhnevets, n.d.).

\[
\text{GEI} = (\text{greenDN} - \text{redDN}) + (\text{greenDN} - \text{blueDN}) \\
= 2 (\text{greenDN}) - (\text{redDN} + \text{blueDN})
\] 

(1)

where DN represents the digital number (channel brightness) for red, green, and blue channels (Richardson et al., 2007).
\[
\text{NDVI} = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})}
\]  \hspace{1cm} (2)

where NIR is the reflectance in near infrared wavelength and RED is the reflectance in red wavelength (Gamon et al., 2006).

\[
\text{GCC} = \frac{\text{DNG}}{\text{DNR} + \text{DNG} + \text{DNB}}
\]  \hspace{1cm} (3)

where DN represents the digital numbers for red (R), green (G), and blue (B) channels (Toomey et al., 2015).
HSV color model:

![HSV Color Model Diagram]

**Figure 1.3**: HSV color model, H=hue, S=saturation, and V=value (Barsky, n.d.).

Although the HSV color model has been rarely explored in phenological studies, there are several studies that demonstrate potential utility beyond the capacity of the RGB color space. HSV (hue, saturation, and value – a transformation of the RGB color model) will be used in this study to determine its capacity for capturing specific plant and landscape phenological trends (see Chapter 3). HSV is based on a different concept to the RGB color model and represents colors in their purest form that can be most effectively visualized as an inverse cone (Figure 1.3) (Proulx & Parrott, 2008). Hue (H) is the specific color that is being displayed that can be seen along the perimeter (circumference) of the cone in (Figure 1.3) (Crimmins & Crimmins, 2008; Smith, 1978). Once the specific color is identified, saturation (S) is calculated and represents how rich the color is. In other words, the higher the saturation value the more washed out the color will appear. High S values can be seen closest to the central axis of the cone visualizing HSV color space in Figure 1.3 and low S values can be seen closest to the perimeter of the cone.
where colors are the most ‘pure’ (Figure 1.3) (Crimmins & Crimmins, 2008; Smith, 1978). Value (V) represents the richness of the color and can range from pure black (the peak of the cone ~ low richness) to high richness at the plane of the cone where color is most ‘pure’ (Crimmins & Crimmins, 2008; Smith, 1978). Although the previously mentioned RGB indices (GEI, NDVI, and GCC) are frequently used for phenological studies, HSV has also been explored and proven in some cases to be more reliable than RGB color space under certain circumstances (Benton, 2009; Crimmins & Crimmins, 2008; Pekel et al., 2014). Benton (2009) found that hue was optimal for the detection of creosote bush flowering. Hue sometimes overestimated the number of flowers present, but was more accurate than RGB color space options investigated (Benton 2009).

**L*a*b* color model:**

*Figure 1.4: L*a*b* color model. L* corresponds to the lightness or darkness in the image. Channels a* and b* represent the opponent color theory for red and green & blue and yellow, respectively (image: http://dba.med.sc.edu/price/irf/Adobe_tg/models/cielab.html).*
L*a*b* (luminance, channel a, and channel b, respectively; Figure 1.4) will be used to determine the efficiency in capturing specific growth patterns in plant phenology (see Chapter 3 below). This color model is based on opponent-color theory which reflects more closely the human perception of colors. L* measures the reflectance properties of a pixel - how light or dark the image is; channel a* represents the color gained from the red and green opponent colors, and channel b* represents the resultant color from the opponent colors yellow and blue (Connolly & Fliess, 1997; Hill et al., 1997). There appears to be no published research that has explored the utility of L*a*b* the color model in phenological studies, suggesting that the study completed in Chapter 3 below may be pioneering this research.

1.1.4. Review and challenges of phenological studies in drylands

One of the historical and still current data collection methods include human observations, which requires individuals to observe and record growth stages of given plant species with datasheets developed by entities such as the National Phenology Network (NPN), the National Ecological Observatory Network (NEON) and ProjectBudBurst. The terminologies and definitions developed by the NPN has created a level of consistency evident across data collectors and has helped make data collection and dispersion possible to a wide range of interest groups (Denny, 2012; Richardson et al., 2007). Since accuracy and consistency are critical to recording plant phenophases, data collection methods expanded to remotely sensed methods, such as time lapse images acquired on phenocams are helping to capture phenological variance in a range of ecosystems (Benton, 2009; Richardson et al., 2007; Toomey et al., 2015). Various remote sensing techniques (e.g. NDVI from satellite imagery) have been used in many plant phenological studies, and have shown a strong relationship between the timing of key growth
stages and climate variability at the regional and global scale (Justice et al., 1985; Keenan et al., 2014; Migliavacca et al., 2011).

Dryland plant phenology studies have been conducted across the globe, and generally support forecasts of dryland ecosystem expansion (Archer et al., 2000; Naito & Cairns, 2011; Van Auken, 2009). In addition to the heterogeneous spatial distribution of plants in drylands, which often creates for phenological studies (Browning et al., 2012; Walker et al., 2014), other research hurdles include: a low abundance of historical and present dryland research relative to ecosystems such as rainforest or temperate forests; and the strong dependence of dryland phenophase development on precipitation that is uncommon and spatially heterogeneous in drylands making some phenophase shifts difficult to determine (Gibbens, 1991; Reynolds et al., 2004). Often, it is difficult for satellite based imagery to detect subtle phenophase shifts due to the high occurrence bare ground in drylands (Walker et al., 2012), which can be overcome through regular ground-based measurements (i.e. human observations) to calibrate/verify more broad-scale remotely sensed data (satellite images) (Badeck et al., 2004; Vilhar et al., 2013). Although human observations are susceptible to high levels of subjectivity, observations of this kind have proven useful for calibrating other methods in order to useful remote sensing techniques that can be applied at a broader scales and across biomes (Graham et al., 2009; Mbow et al., 2013).

Readily available historical dryland plant phenology research does not compare to that of other ecosystems such as, temperate or rainforest biomes (Richardson et al., 2007; Yanoff & Muldavin, 2008). When using key words to search for relevant studies within the Science Direct database, the number of papers located for “temperate plant phenology” or “rainforest plant
phenology” resulted in over 4,000 studies; whereas, the number of papers relevant to “dryland plant phenology” only results in about 700 papers (Science Direct). Another possible contribution to the lack of attention drylands have received may be that dryland phenophase transitions rely heavily on certain climatic events, such as rainfall, which can be sporadic and uncommon in drylands making detection of key phenophase shifts difficult (Munson et al., 2015; Walker, 2014; Yanoff & Muldavin, 2008). In other biomes, phenophase shifts appear to be controlled by temperature and photoperiod, which are more readily measured and consistent from year to year (Kramer et al., 2000; Melaas et al., 2013; Piao et al., 2007; Richardson et al., 2007).

1.2. Goals and objectives

The overarching goal of this study is to determine the spatial and temporal dynamics of plant phenology in different land cover types of a northern Chihuahuan Desert landscape. To achieve this goal the study links: (1) conventional phenocam-derived analysis of species and landscape plant phenology in different land cover types with, (2) a novel analysis of phenocam imagery that utilizes alternate color space. Specifically, this study will address the following questions in two primary chapters (Questions 1 and 2 ~ Chapter 2, Question 3 ~ Chapter 3):

1. Is landscape plant phenology spatially variable across a Chihuahuan Desert landscape?
2. Do different plant species drive greening trends in different land cover types?
3. Does phenological analysis with alternate color space offer advantages over customary approaches that utilize only RGB color space?
1.3. Study Area

This study was performed on the United States Department of Agriculture-Agricultural Research Services (USDA-ARS) Jornada Experimental Range (JER; Figure 1.5) that hosts the Jornada Basin Long Term Ecological Research (LTER) site and encompasses an approximate area of 200,000 ha in Doña Ana County, southern New Mexico, USA in the northern Chihuahuan Desert, the largest desert in North America (Figure 1.5) (Campbell, 1929; Herrick et al., 2006; Peters et al., 2013). Although the JER can be considered a shrubland as a whole, with Creosotebush (*Larrea tridentata*) and Mesquite (*Prosopis glandulosa*) as the two dominant plant species, there are still a variety of land cover types (LCT) present. In Chapter two, this study focuses on four different plant communities (land cover types) commonly found throughout the Chihuahuan Desert: shrubland, shrubland-sandy ridge, grassland-tobosa playa, and grassland (Figure 1.6) (Peters et al., 2006). Subtle differences in elevation, soil composition, plant population, soil permeability, and other variables can change the LCT for a given area (Peters and Gibbens, 2006; Peters et al., 2013). The advantage of examining phenological trends in these different land cover types is that research findings can be extrapolated regionally using land cover maps.
Figure 1.5: The USDA-ARS JER near Las Cruces, New Mexico. This JER research range is managed by the New Mexico State University (NMSU). Map courtesy of (jornada-www.nmsu.edu).
1.3.1. Climate

The Climatic record for the JER dates back to 1915, making this an ideal location for long-term research. The Chihuahuan desert is the largest desert in North America and is located in the rain shadow of the Sierra Madre Occidental and the Sierra Madre Oriental, which flank the western and eastern edges of the desert, respectively (Shmida et al., 1985; Sowell, 2001). Based on the Koppen classification the JER is a mid-latitude (cold) desert (Havstad et al., 2006) due to its high solar radiation, low relative humidity, wide ranges in diurnal temperatures, variability in annual precipitation, and high rates of evaporation, which surpasses precipitation allowing a moisture deficit to persist. The JER has a mean annual air temperature of 15°C and a mean annual precipitation of approximately 250 mm, most of which falls as rainfall in late summer monsoons that are common between July and September (Bestelmeyer et al., 2013; Havstad et al., 2006).

1.3.2. Landscape

The JER (783 km$^2$) is located in Southern New Mexico within the Chihuahuan Desert (Havstad et al., 2000). Landforms include, but are not limited to, rocky mountain slopes, stony bajadas, and silty basin floors (Monger, 2006). Soil development since the Quaternary has been influenced by fluctuations in climate, parent material and topographical position (Gile et al., 1981; Monger, 2006). The JER has a slightly sloping surface that is modified by winds and creates the coppice dunes seen throughout the range. As classified by the USDA ARS JER habitats of the JER are regionally representative of the northern Chihuahuan Desert (Havstad et al., 2006).
1.3.3. Vegetation

Grasslands flourished throughout the American south-west over 150 years ago (Ares et al., 1974; Bhark & Small, 2003; Dick-peddie, 1975); however, with extensive land settlement and grazing between the late 1800’s and mid 1900’s (Ares et al., 1974) and persistent drought during the 1950’s, the abundance of grass cover has decreased in the region (Gibbens & Beck, 1988). Generally, the plant communities in the region are classified as desert-grassland transition (Peters and Gibbens, 2006). The JER, specifically, has been classified as having five major land cover types (Peters and Gibbens, 2006) which include: [1] grasslands dominated by Black Grama (Bouteloua eriopoda), [2] playa grasslands, shrublands dominated by [3] Tarbush (Flourensia cernua), or [4] Creosotebush (Larrea tridentata), or [5] Honey Mesquite (Prosopis glandulosa).

For this study, eight key plant species that are common throughout the Chihuahuan Desert were selected for observation. The species are as follows: Honey Mesquite (Prosopis glandulosa), Creosotebush (Larrea tridentata), Tarbush (Flourensia cernua), Bush Muhly (Muhlenbergia porterii), Mesa Dropseed (Sporobolus flexuosus), Tobosa Grass (Pleuraphis mutica), Fluff Grass (Dasyochloa pulchella), and Black Grama (Bouteloua eriopoda). The following sections briefly outline the distinguishing biological characteristics for each of these species (Table 1.1).
Table 1.1: Focal plant species monitored in this study. Sites can be seen in Figure 2.3, above. Taxonomy is derived from the USDA Plant Database (http://plants.usda.gov/java/).

<table>
<thead>
<tr>
<th>Genus name</th>
<th>Species name</th>
<th>Code</th>
<th>Common name</th>
<th>Land cover type</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Prosopis</em></td>
<td>glandulosa</td>
<td>PRGL</td>
<td>honey mesquite</td>
<td>shrubland, shrubland-sandy ridge, grassland-tobosa playa, and grassland</td>
<td>All</td>
</tr>
<tr>
<td><em>Larrea</em></td>
<td>tridentata</td>
<td>LATR</td>
<td>creosote bush</td>
<td>shrubland and shrubland-sandy ridge</td>
<td>TWEE, TROM, &amp; SCAN2</td>
</tr>
<tr>
<td><em>Flourensia</em></td>
<td>cernua</td>
<td>FLCE</td>
<td>tarbush</td>
<td>shrubland</td>
<td>TWEE &amp; TROM</td>
</tr>
<tr>
<td><em>Muhlenbergia</em></td>
<td>porteri</td>
<td>MUPO</td>
<td>bush muhly</td>
<td>shrubland</td>
<td>TWEE &amp; TROM</td>
</tr>
<tr>
<td><em>Pleuraphis</em></td>
<td>mutica</td>
<td>PLMU</td>
<td>tobosa grass</td>
<td>grassland-tobosa playa</td>
<td>SCAN1</td>
</tr>
<tr>
<td><em>Sporobolus</em></td>
<td>flexuosus</td>
<td>SPFL</td>
<td>mesa dropseed</td>
<td>grassland-tobosa playa and grassland</td>
<td>SCAN1, PAS9, &amp; IBPE</td>
</tr>
<tr>
<td><em>Dasyochloa</em></td>
<td>pulchella</td>
<td>DAPU</td>
<td>fluff grass</td>
<td>shrubland</td>
<td>TWEE &amp; TROM</td>
</tr>
<tr>
<td><em>Bouteloua</em></td>
<td>eriopoda</td>
<td>BOER</td>
<td>black grama</td>
<td>grassland</td>
<td>PAS9 &amp; IBPE</td>
</tr>
</tbody>
</table>
Honey Mesquite (*Prosopis glandulosa*)

Knowledge of the physical appearance and temporal emergence of key phenophases of any plant species is critical for accurate observation and record keeping, which will be briefly covered for each of the following species. *Prosopis glandulosa* (honey mesquite) is a C\textsubscript{3} deciduous shrub and lives for approximately 200 years (Figure 1.7) (Peters and Gibbens, 2006). Honey mesquite is a member of the Fabaceae (legume) family, and can occupy about 30-55\% of the plant land cover for plant communities in which it dominates (honey mesquite shrublands or shrublands) (Peters and Gibbens, 2006). Honey mesquite has very extensive and deep roots (Gibbens & Lenz, 2001a) and is present throughout the JER but is most common on gravelly/sandy soils (Havstad \textit{et al.}, 2006). Honey mesquite can grow to heights of about 6m tall, but has been documented to have a greater total biomass below-ground then above-ground (Gibbens & Lenz, 2001a). When not managed in grazed rangelands, honey mesquite can be an aggressively invasive that displaces other native species that are not as tolerant to disturbance (Moran \textit{et al.}, 1993). This feature in part explains the extensive expansion of this and other grazing-tolerant shrub species in southwest rangelands over past century (“Desert Plants…,” n.d.). Honey mesquite has the capacity to form symbiotic relationships with N-fixing bacteria (Geesing \textit{et al.}, 2000).

One or two spines can be seen at each node and leaves are alternate and bipinnate. There is one paired division per leaf and about 6 to 15 leaflets (15 to 62 mm long) per pinna (“Welcome to…,” n.d.). Leaves bud in late spring/early summer. Commonly, leaves reach full size 45 to 60 days after bud break. Flowers typically bloom from spring into summer and resemble yellowish tiny frothy-like clusters of flowers called catkins ("Plants &…," n.d.). Seedpods are 7 to 20 cm long with a reddish-brown tint and inside are the brown seeds that reach 6 to 7 mm in length.
Honey mesquite seeds are vital energy sources for some small and large mammals such as, jack rabbits and cattle. When milled, humans can also use these seeds as meal or flour (“Plants &…,” n.d.). Numerous bird species are known to nest in the canopy of honey mesquite and are benefited from the height advantage and protection these plants offer (“Desert Plants…,” n.d.). Honey mesquite is expansive and highly tolerant of dryland conditions, making it an important plant species in southwest dryland ecosystem studies.

**Creosotebush (*Larrea tridentata*)**

*Larrea tridentata* (creosote bush) is an evergreen long-lived C₃ perennial shrub (Figure 1.8) (Miller & Huenneke, 2000) that is common throughout the U.S. Southwest drylands (Reynolds, 1986), especially on well drained slopes and plains where caliche is present. It can occupy about 28–45% of the land cover within a given LCT (Peters and Gibbens, 2006). Creosote bush also prefers more porous soils unlike honey mesquite (Hamerlynck *et al.*, 2000). Its adaptation to these water limited environments mostly come from physiological adaptations (Waide *et al.*, 1999). creosote bush also has a deep, wide spread, and non-overlapping root system (Hamerlynck *et al.*, 2000). Even when under water stress, creosote bush can maintain relatively high photosynthetic rates year-round (Franco *et al.*, 1994; Odening *et al.*, 1974) making this species a hardy in dryland environments. creosote bush is prominently featured in Whitford’s (*et al.*, 1997) theory of ‘*islands of fertility*’ which proposes that due to a combination of canopy architecture, nutrient uptake, litter fall, and shrub interspace soil erosion, water accumulates underneath the canopies of creosote bush promoting nutrient uptake and enhanced plant growth (Whitford *et al.*, 1997).
Creosote bush has a large number of medium to large sized flexible branches extending from the base of the shrub and reaching a height of 1.2 m although it rarely grows up to 3.6 m (Federal Forest Services). Leaves on creosote bush are usually about 0.6 to 1.2 cm in length and can bud at various times throughout the year, although they do stop budding and/or drop some of their leaves in extreme conditions (drought or frost) (Federal Forest Services). Yellow flowers bloom from February-August when ideal growing conditions prevail (Federal Forest Services). From the center of the flowers a small greenish fuzzy ball shaped fruit with five sections emerges. When fruits mature and turn a brown color, they dehisce, and drop five individual ripe fruits (Federal Forest Services).

**Tarbush (Flourensia cernua)**

Flourensia cernua (tarbush) is a C₃ perennial shrub. It is typically found in arroyos where there is a higher prevalence of soil water (Figure 1.10), but can also be common near playas on clay/silt soils (Peters et al., 2006) and areas with predominantly bare ground with dispersed shrubs and grasses. Sometimes tarbush can be known to smell like tar as a result of out-gassing of secondary compounds found in the leaves (Estell et al., 1998). It also has an elaborate root system that allows it to acquire water both deep in the soil and near the soil surface (Gibbens & Lenz, 2001b). It can tolerate flooding but only for a short amount of time (Dick-Peddie, 1993). Instead of a trunk, tarbush has branches that extend obliquely from the base and can grow up to 2 m tall. Tarbush has smooth, dark green leaves that are alternate and range from 1.7 to 2.5 cm in length and 1 cm in width (“Plants &…,” n.d.). Flowers on tarbush are yellow, small, single, and often difficult to see and occur in late spring. Each flower head has up to 20 flowers and the seeds are flattened and hairy achenes.
**Bush Muhly (Muhlenbergia porteri)**

*Muhlenbergia porteri* (bush muhly) is a C₄ perennial grass and is most common between boulders, cliffs, in between shrubs, near dry arroyos, and in some grassland (Figure 1.9). It is grazed on by cattle (Miller & Donart, 1981; “Plants &…,” n.d.; “Welcome to…,” n.d.) and can be heavily grazed during the winter when the availability of other grasses is sparse (Miller & Donart, 1981). It can be seen most commonly underneath honey mesquite or creosote bush (Chew, 1982; Miller & Donart, 1981) as described by the ‘islands of fertility’ hypothesis (Whitford *et al.*, 1997) discussed above. It can reach heights from 25 to 100 cm tall. Initial leaf growth in bush muhly can be seen in early spring to late summer and flowering can be seen in early spring and summer (Kemp, 1983; Livingston *et al.*, 1995). Leaf blades are usually flat or folded, 0.5 to 2 mm wide, and usually rough in texture (“Plants &…,” n.d.). Flowers are fine, many-branched, purplish, and when it is in full bloom the entire plant can have a cobwebby appearance.

**Tobosa Grass (Pleuraphis mutica)**

*Pleuraphis mutica* (tobosa grass) is a perennial grass (Figure 1.11). Tobosa grass is also heavily grazed on by cattle and horses (“Welcome to…,” n.d.), but can recover from grazing relatively quickly (“Plants &…,” n.d.). This grass grows best on clay-like soils and slopes. Roots for tobosa grass are shallow and can extend from 0.6 to 1.8 m in depth (“Plants &…,” n.d.). This is an erect grass that can to grow to approximately 0.6 m at maturity (“Welcome to…,” n.d.). Its active growth period falls between spring and summer and can produce light yellow flowers, with ripe brown seed color that follows flowering. Its seed production begins mid-late summer and ends in the fall (“Welcome to…,” n.d.).
Mesa Dropseed (*Sporobolus flexuosus*)

*Sporobolus flexuosus* (mesa dropseed) is a perennial grass (Figure 1.12) and is most common on sandy and/or loamy soils with a preference for well-drained soils (“Welcome to…,” n.d.). Mesa dropseed are short-lived (4-5 years) perennials and greens up during the spring, and if the conditions are ideal, again in late fall. During extreme drought periods, mesa dropseed goes into dormancy. Culms can grow up to 2 m tall. The growing season for this grass is from March through November. Mesa dropseed produces hermaphrodite inflorescences in late fall (September to November) (Gibbens, 1991). Seeds are open, oblong panicles that can grow to 10-30 cm long (“Plants &…,” n.d.). Mesa dropseed has one floret that produces one small seed with a hard coat.

Fluff Grass (*Dasyochloa pulchella*)

*Dasyochloa pulchella* (fluff grass) is also a C₄ perennial grass (Figure 1.14). This grass is a colonizing species with a short-lived life cycle typically found on gravelly soils in ecosystems with a high percentage of bare ground (Pezzani *et al.*, 2006). It can form open mats and is weakly rooted (“Plants &…,” n.d.). In its initial growth the leaves are light green, and once they have matured turn into a green whitish color. The clusters usually bend over to the ground and root themselves (“Plants &…,” n.d.). This grass displays an erect growth pattern that forms culms 4 to 10 cm in height. Their “fluffy” appearance develops at the maturity of their growth stage and is caused by fascicled spikelets with white hairs (Powell, 1998). It has 1-5 spikelets which are attached to the rachis and contain 5-10 florets. Flowering occurs mid-July through mid-September.
Black Grama (*Bouteloua eriopoda*)

*Bouteloua eriopoda* (black grama) is a perennial grass (Figure 1.13) that is widely regarded as a major source of fodder for livestock in the southwest U.S. where it is sometimes cut for hay (USDA-plants). Black grama mostly grows in gravelly soils, sandy dunes, and is seldom seen in clay soils (USDA-plants), in contrast to the other grasses examined in this study. Black grama forms a weak sod and roots at the nodes of the stems and is an ideal species to prevent soil erosion (Federal Forest Services). The leaf blade can grow from 25 to 71 cm in height and can roll inwards during drier periods (USDA-plants). The stem is solid and the seed-head has 3 to 8 spikes per head and 18 to 20 spikelets per spike (USDA-plants). In order to have successful asexual reproduction by stoloniferous growth, the plant generally requires two successive favorable growing seasons (USDA-plants).
Figure 1.7: A-B. A. U.S. distribution map of the shrub Prosopis glandulosa - honey mesquite (USDA Plants Database), B. honey mesquite on the JER displaying full leaf extension (photo taken: August 2013).

Figure 1.8: A-B. A. U.S. distribution map of the evergreen Larrea tridentata - creosote bush (USDA Plants Database), B. creosote bush at the JER displaying young unfolded leaves (photo taken: June 2013).
Figure 1.9: A-B. A. U.S. distribution map of the deciduous shrub Flourensia cernua - tarbush (USDA Plants Database), B. tarbush at the JER displaying flower buds (photo taken: September 2013).

Figure 1.10: A-B. A. U.S. distribution map of the grass Muhlenbergia porteri - bush muhly (USDA Plants Database), B. Bush muhly at the JER displaying ripe grains (photo taken: August 2014).
Figure 1.11: A-B. A. U.S. distribution map of the grass Pleuraphis mutica - tobosa grass (USDA Plants Database), B. tobosa grass at the JER displaying initial leaf growth and tall shoots of grass blades (photo taken: August 2014).

Figure 1.12: A-B. A. U.S. distribution map of the grass Sporobolus flexuosus - mesa dropseed (USDA Plants Database), B. Mesa dropseed at the JER displaying ripe grains (photo taken: August 2014).
Figure 1.13: A-B. A. U.S. distribution map of the grass Dasyochloa pulchella - fluff grass (USDA Plants Database), B. fluff grass at the JER displaying flower heads (photo taken: August 2015).

Figure 1.14: A-B. A. U.S. distribution map of the grass Bouteloua eriopoda - black grama (USDA Plants Database), B. Black grama at the JER displaying flower heads (photo from: museum2.utep.edu).
2. **Inter-comparison of plant and landscape phenology in different land cover types on the Jornada Experimental Range**

2.1 **Introduction**

Monitoring and understanding phenology trends in drylands are critical for predicting the type of impact this ecosystem will have on regional and global scale atmospheric carbon cycling (Gao & Reynolds, 2003; Migliavacca *et al.*, 2011). When compared to other systems, dryland plant phenological studies and its contribution to these land atmosphere interactions have not been as heavily explored (Kurc & Benton, 2010). Since drylands cover about 40% of the Earth’s land surface, and are predicted to significantly expand over the next few decades (Peters *et al.*, 2006; Poulter *et al.*, 2014; Reynolds *et al.*, 2007) improving our understanding of the spatiotemporal dynamics and the controls of phenology are paramount for improving land-management, modeling future ecosystem states, and understanding how change in drylands may impact the Earth System. This chapter uses remote sensing techniques commonly practiced for studies similar to this; specifically, time lapse images analysis was used to capture greening trends from 2012 to 2015. Greening trends at the species level were compared to landscape level greening with the aim of capturing species drivers and contributors of overall landscape greening, in other words, this comparison will give insight to suggest which plant species have more influence on landscape level greening.

2.2 **Methods**

This study spanned four land cover types (LCTs) on the Jornada Experimental Range (JER; Figure 1.6), which were chosen to represent the variety of LCTs seen more broadly throughout the Chihuahuan Desert. Phenocams were used to capture images at regular intervals at each site.
(Table 2.1). Images captured at solar noon were used in analyses to minimize the potential of shading in the field of view and both limit complications associated with differences in sun angle in analyses, and more accurately represent phenological trends across LCTs. Images from the Wingscape cameras have shown to display degradation in the quality of the images over time with a shadow gradient that required pre-processing before any analysis could be performed (Figure 2.1).

Collaboration with the Department of Computer Science and UTEP’s Cyber-ShARE Center for Excellence has assisted the study develop a program within MatLab that can calibrate, correct, and process the images. Dr. Geovany Ramirez, a former doctoral graduate in computer science, collaboratively developed this software (hereafter Phenology Analyzer Software or PAS). In order to calibrate the images, we captured images of a near-perfect white board for each camera to quantify the shadow gradient. A model of this gradient was generated to visualize the error, and in order to correct this gradient, a gradient with opposite color values was laid on top of the first model Figure 2.2. After calibration, the software can automatically correct all the images in a specified directory (Figure 2.3) and save the new images into a different directory to avoid overwriting original images. Image analysis was performed with the PAS that allows users to apply multiple regions of interest (ROIs) of different shapes and sizes, and to save ROIs for future use and reference (Figure 2.4 a & b). PAS also allows users to view images with multiple color spaces such as the ones previously mentioned: RGB, HSV, and L*a*b*. These alternate color spaces will be explored in the next chapter. Once the all images have been calibrated, corrected, and processed with PAS (Figure 2.5 a-f) the values are saved as a csv file where more statistical analysis can be performed.
This section of the study aims (1) to determine if there is any spatial variability in landscape plant phenology across LCTs, and (2) to determine if there are specific plant species that seem to drive plant phenology within each LCT. Specific landscape and individual plant species ROIs were chosen for Objective 1 (Figure 2.5 a-f) and processed with PAS. Landscape ROIs were chosen to include the top half of the landscape within the field of view (excluding the sky), which captures vegetation representative of each LCT and omits most bare ground captured in the lower half of the field of view (Fig. 2.5 a-f). Species specific ROIs were chosen based on which plants within the field of view were most visible and had the least amount of overlap from other plants in order to best represent each species (Fig. 2.5 a-f). After the images were processed for all hours, a filter was used to include only images captured at noon (solar zenith angle; solar noon) to minimize shadowing and challenges in image analysis associated with shifts in sun angle (Keenan et al., 2014; Peters et al., 2014). The same process was used for both the landscape and species specific comparisons. The green chromatic coordinate (GCC) index (Ahrends et al., 2008; Richardson et al., 2007; Sonnentag et al., 2012; Toomey et al., 2015) was used to determine phenological changes across four years of phenocam images acquired as described above, phenological trends will be referenced as ‘GCC’ from this point forward.

This formula - derived from the standard red, green, and blue (RGB) color model has been used in multiple studies, including dryland studies to show seasonal change in vegetation phenology and thus represents a proven metric suitable for inter-comparison between ecosystems and studies. GCC was used to plot phenological trends at the landscape and species level for each of the LCTs as shown below (Fig. 2.7- 2.14). Scatter plots were created for each of the ROIs (Fig. 2.5a-f) with a 28-day running average plotted on top to help visualize trends. Figure 2.7 displays the landscape level phenological trends captured with time lapse images along with daily
precipitation, which has been shown to be an important driver of greening trends in dryland ecosystems (Lesica & Kittelson, 2010; Ogle & Reynolds, 2004).

Table 2.1: Cameras used to address objectives one and two. Only photos captured at solar noon were used for this project to reduce shading and other complications associated with the analysis of imagery acquired at different sun angles.

<table>
<thead>
<tr>
<th>Site</th>
<th>LCT</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Years</th>
<th>Camera</th>
<th>pixel</th>
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<td>Windscapers “PlantCams”</td>
<td>4 MP</td>
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<td>-106.64547</td>
<td>2012-2015</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Eddy Tower Phenocam

| cam2 | SBL | 32.58196 | -106.63503 | 2010-ongoing | Microsoft webcam model Vx7000 | 2 MP | Gonzalez, 2011 |

Note: SBL = shrubland, GTP = grassland-tobosa playa, SSR = shrubland-sandy ridge, GRL = grassland

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Figure 2.1: Image depicting the color gradient (area enclosed in red rectangle) for the TWEE site. All cameras displayed a similar error and were corrected independently.

Figure 2.2: A model of the calibration process with the Phenology Analyzer Software, which identified and corrected the shadow gradient (enclosed in the red rectangle) displayed in the TWEE image (Fig. 2.1). [1] ‘Calibration Image’ captured a pure white panel by the camera - red rectangle is the same area as displayed in Fig. 2.1 which depicts the gradient issue; [2] The ‘Illumination Model’ is the visual model generated from the white panel image; [3] The ‘Compensation Image’ is the same gradient from ‘Illumination Model’, but with opposite values.
Figure 2.3: A model of the Phenology Analyzer Software correcting the TWEE images from [1] specified directory; [2] Original image (gradient enclosed in red rectangle) and the [3] corrected image (fixed gradient enclosed in red rectangle); There is also the option to correct the images in a [4] ‘Raw’ or ‘Normalized’ process which can then be [5] stored in a new directory.

Figure 2.4 a&b: A screen shot of the Phenology Analyzer Software processing images for the TWEE site. Images were used from the directory occupied with corrected images (step 5 in Fig. 2.3). [1] ‘Directory’ which the PAS will use to load all images to be processed; [2] Multiple color spaces included in the analysis; [3] An ROI can either be a rectangle, ellipse, polygonal shape, or a free-hand shape. Each can be saved and stored for future use; [4] ‘Live View’ shows the real time values for each color option; [5] ‘Plots’ generates a quick and dirty plot for any of the options selected; [6] ‘Save Data’ will save the values generated from the ROIs into a .csv file; [7] A rectangular ROI was chosen to represent the landscape phenological phases; and [8] free-hand ROIs were carefully chosen and outlined to represent the phenological phases for Honey Mesquite within this LCT.
Figure 2.5 a-f: Regions of interest (ROI) used for landscape and species specific phenology. White = landscape; green = honey mesquite; orange = mesa dropseed; pink = black grama; pink (dashed) = mix of black grama and mesa dropseed; purple = tobosa grass; blue = tarbush; red = creosote bush; red (dashed) = mix of creosote bush and tarbush; yellow = bush muhly. (a) IBPE1 ROIs – grassland; (b) PAS9 ROIs – grassland; (c) SCAN1 ROIs – grassland-tobosa playa; (d) SCAN2 ROIs – shrubland-sandy ridge; (e) TROM ROIs – shrubland; and (f) TWEE ROIs – shrubland.
2.3 Results

TROM is a creosotebush-honey mesquite shrubland site with bush muhly growing in shrub interspaces (Figure 2.5 e). Similar to all LCTs, except SCAN2, TROM displayed a generally broad peak during the growing season of 2012 that consisted of three separate spikes in GCC between July and September, which was not evident in 2013 or 2014 for this LCT (Figure 2.7). Each of these spikes in GCC followed three rain events that occurred about 1-2 weeks prior to peaks in GCC. In 2013, there was an early GCC peak (mid-June) that preceded the first rainfall events for the year. After the rainfall events occurred between July through August, TROM peaked in GCC from September through October. In 2014, another early spike in GCC was captured mid-June which did not seem to follow any precipitation events. This was the last peak in GCC captured for TROM before the camera no longer functioned (Figure 2.7).

TWEE is also a creosote-honey mesquite shrubland site with bush muhly intertwined beneath the canopies of shrubs with bare ground exposed between shrubs (Figure 2.5 f). TWEE also displayed three peaks in GCC that like TROM followed three separate rainfall events. In 2013, an early peak in GCC was captured that did not seem to follow any significant precipitation events. The second peak in 2013 was also seen in September/October (as in TROM) after heavy rainfall events in the preceding months. In 2014, there was another early peak in GCC at TWEE, which occurred in mid-June and did (similar to 2013) not follow any heavy precipitation (Figure 2.7). Towards the end of October there was another peak in GCC for TWEE, but this peak (unlike the first) did follow a precipitation event (Figure 2.7). Similar patterns were also seen in 2015, until the camera stopped working in mid-August.
SCAN1 - grassland-tobosa playa - displays almost no bare ground and is dominated by tobosa grass with scattered honey mesquite (Figure 2.5 c). SCAN2 - shrubland-sandy ridge – has more bare ground exposure than SCAN1, but is still dominated by tobosa grass with scattered establishments of honey mesquite, tarbush, and creosotebush (Figure 2.5 d). SCAN1 and SCAN2 displayed similar trends in generalized landscape GCC greening and browning trends across all years (Figure 2.7). SCAN1 displays one clear peak in GCC in 2012, which occurs around the same time as that for TWEE, PAS9, and IBPE1; however, it does not display a prominent second peak in GCC that year like other LCTs (Figure 2.7). During 2013 - 2015, peaks in GCC occurred slightly ahead of those for other LCTs (mid-late August). Unlike GCC trends in other sites, there was a negligible seasonal shift in GCC for 2012 (Figure 2.7). During 2013 and 2014, peaks in GCC aligned well with trends documented for the other LCTs (Figure 2.7). The camera ceased functioning in spring 2015 for SCAN2.

PAS9 and IBPE1 display a low amount of bare ground and include the same dominant plant species - black grama, mesa dropseed, and honey mesquite (Figure 2.5 b & a, respectively). These grassland sites displayed similar patterns in GCC, but the camera at PAS9 did not function after mid-2014. The two peaks in GCC (June and August) were evident for both grassland sites in both 2012 and 2013 (Figure 2.7). IBPE1 continued recording through 2015 and resulted in GCC peaks around mid-late August for both 2014 and 2015 (Figure 2.7).

Precipitation is a limiting factor for plant life in drylands which can directly affect phenology which may result in shifts throughout trophic levels. 2012 and 2013 experienced very few rain events (drought years) which led to a low amount of annual cumulative precipitation especially when compared to the proceeding years (Figure 2.6). 2013 experienced a few more intense
rainfall events with the highest input of 42 mm in September. 2014 and 2015 both received noticeably more rainfall events than 2012 and 2013, making these years ‘abnormally wet years’ (Figure 2.6). The highest rainfall event in 2014 was about 45 mm in late September. Although 2015 did not receive as many intense precipitation events as 2014, rainfall input was more consistent throughout the year (Figure 2.6).

![Figure 2.6: Daily and cumulative rainfall (mm) for 2012-2015. MOY = month of the year.](image1)

**Figure 2.6:** Daily and cumulative rainfall (mm) for 2012-2015. MOY = month of the year.

![Figure 2.7: Landscape phenology trends across all land cover types (LCTs) from 2012-2015. Each LCT scatter plot has a 28-day moving average trend line set on top. TROM = black; TWEE = red; SCAN1 = green; SCAN2 = purple; PAS9 = yellow; IBPE1 = blue.](image2)

**Figure 2.7:** Landscape phenology trends across all land cover types (LCTs) from 2012-2015. Each LCT scatter plot has a 28-day moving average trend line set on top. TROM = black; TWEE = red; SCAN1 = green; SCAN2 = purple; PAS9 = yellow; IBPE1 = blue.
Since honey mesquite (C₃ shrub) and warm season C₄ graminoid species were present at all six sites, this allowed the study to explore these trends across all sites for similarities or dissimilarities (Figure 2.8 a&b). For the most part, GCC trends for honey mesquite and graminoids were consistent across all LCTs (Figure 2.8 a), meaning that the timing of peaks in maximum greening captured by the cameras were similar across sites for each species. There were at least two separate and distinct peaks in 2012 for both honey mesquite and graminoid GCC values (mid-July and mid-September) with the exception of TROM, which captured three peaks (July-September). SCAN2 did not see any peaks in GCC for 2012 and retained a comparatively flat line all year (Figure 2.8 a). There was another early peak in GCC for honey mesquite seen across all LCTs in 2013 around mid-June. The three peaks in greening can also be seen for graminoid species in 2012, but only for the TROM site. All other LCTs seemed to stay flat until the next peak in productivity in mid-September (Figure 2.8 b), which was also captured for honey mesquite (Figure 2.8 a).

2014 honey mesquite productivity seemed to repeat the same pattern observed in 2013, displaying an early peak in GCC (Figure 2.8 a) with the exception of SCAN2, which remained flat until the occurrence of precipitation events during September (Figure 2.8 b). Both the TROM and PAS9 cameras ceased working mid-August. In 2014, GCC for honey mesquite at TWEE, IBPE1, and SCAN1, no second peak in greenness was observed. Although there was no early peak in GCC for graminoid species, there was a peak in GCC after the rainfall events that occurred between July and September 2014. Rainfall events in 2015 were followed by peaks in GCC for honey mesquite and graminoid species at the TWEE, SCAN2, and IBPE1 sites (Figure 2.8 a & b).
Figure 2.8 a&b: Phenology trends (GCC) for honey mesquite and graminoids observed in all LCTs. (a) Shrub - honey mesquite. (b) GCC values for all graminoids (TROM & TWEE- bush muhly; SCAN1 & SCAN2-tobosa grass; PAS9- mesa dropseed; and IBPE1- black grama / mesa dropseed mix) across all four LCTs. TROM = black; TWEE = red; SCAN2 = purple; SCAN1 = green; PAS9 = yellow; IBPE1 = blue.
In order to determine which plant species appears to drive GCC in each LCT, we plotted landscape GCC (black trend line included across all the LCTs) against GCC values generated for each species. For this section of the results, we will focus on the species specific GCC trends and assess how closely the match landscape trends. At IBPE1, landscape GCC was most strongly aligned with graminoid species GCC - green trend line (Figure 2.9). At PAS9 landscape trends in GCC closely matched GCC trends for mesa dropseed (Figure 2.10). For SCAN1, landscape GCC appeared to be most strongly aligned with trends in tobosa grass (Figure 2.11). At SCAN2 (Figure 2.12) landscape GCC and species specific GCC trend aligned well with all species (tobosa grass, honey mesquite, creosote bush, and tarbush) suggesting that there was no dominant species driving landscape patterns in phenology at this site. TROM landscape GCC aligned with almost all species trends with the exception of creosote bush (Figure 2.13). Some LCTs displayed clear similarities in landscape and species specific GCC trends while others did not. At TWEE, landscape GCC appeared to be controlled by honey mesquite and creosote bush (Figure 2.14).

![Figure 2.9](image-url): Landscape and species 28-day GCC trend lines plotted for IBPE1 (grassland) from 2012-2015. Black = landscape; green = honey mesquite; and pink (dashed) = black grama & mesa dropseed. Blue dashed line is cumulative precipitation for each individual year.
Figure 2.10: Landscape and species 28-day GCC trend lines plotted for PAS9 (grassland) from 2012-2015. **Black** = landscape; **green** = honey mesquite; **pink** = black grama; and **orange** = mesa dropseed. Blue dashed line is cumulative precipitation for each individual year.

Figure 2.11: Landscape and species 28-day GCC trend lines plotted for SCAN1 (grassland-tobosa playa) from 2012-2015. **Black** = landscape; **green** = honey mesquite; and **purple** = tobosa grass. Blue dashed line is cumulative precipitation for each individual year.

Figure 2.12: Landscape and species 28-day GCC trend lines plotted for SCAN2 (shrubland sandy-ridge) from 2012-2015. **Black** = landscape; **green** = honey mesquite; **purple** = tobosa grass; **red** = creosote bush; and **blue** = tarbush. Blue dashed line is cumulative precipitation for each individual year.
Figure 2.13: Landscape and species 28-day GCC trend lines plotted for TROM (shrubland) from 2012-2015. Black = landscape; green = honey mesquite; red = creosote bush; blue = tarbush; red (dashed) = mix of creosote bush and tarbush; and yellow = bush muhly. Blue dashed line is cumulative precipitation for each individual year.

Figure 2.14: Landscape and species 28-day GCC trend lines plotted for TWEE (shrubland) from 2012-2015. Black = landscape; green = honey mesquite; red = creosote bush; and yellow = bush muhly. Blue dashed line is cumulative precipitation for each individual year.
2.4 Discussion

The main goal for this chapter was to document landscape and species-specific greening (GCC) trends across different LCTs commonly seen throughout the JER and northern Chihuahuan Desert (Peters and Gibbens, 2006). More specifically, the aim was to identify species-specific drivers and/or contributors to landscape greening trends within each LCT. When compared to other LCTs, the earlier landscape greening (early June) captured by cameras in the shrubland LCTs was most likely driven by shrub level greening trends which dominate this LCT (Huenneke et al., 2002; Maynard et al., 2016). Since 2012-2013 received little to no rain input in the earlier part of the year, the early peak in greening from shrubs is evidence in its likely ability to access water at deeper soil horizons (coupled with ideal climatic conditions, i.e. temperature) from which initial growth is stimulated (Browning et al., 2012; Gibbens & Lenz, 2001a). This may also be evidence that the productivity of shrubs is also tied to winter water supply and possibly the lower evapotranspiration at this of the year, thus allowing deeper water infiltration and transport by deep rooted plants (Gibbens & Lenz, 2001a; Munson et al., 2013).

During the non-drought years (2014-2015) there is a clear shift in the response time for the first spring green-up events, which can be seen across most non-shrub dominated LCTs (Lesica & Kittelson, 2010; Reynolds et al., 1999). Earlier precipitation events for 2014-2015 resulted in quick responses for overall landscape greening trends which might be attributed to the quick responses commonly seen in grasses (Munson et al., 2013; Walker et al., 2014). Grasses are known for quickly reacting to precipitation events that reach their shallow root systems (Gibbens & Lenz, 2001a; Peters et al., 2010) resulting in greater seasonal fluctuation tied to rainfall events (Peters et al., 2014; Peters et al., 2013). There seemed to be strong ties between earlier greening
events during non-drought years and later greening events during drought years (Munson et al., 2013, 2015).

The grassland-tobosa playa was the only LCT that captured a clear species driver for overall landscape phenology trends. This site is dominated by tobosa grass with few mesquite plants scattered throughout (Peters & Gibbens, 2006); therefore, the cameras were likely able to capture the greening signatures from the greater species coverage of tobosa grass over shrubs, resulting in similar greening trend lines at the species and landscape level. Due to the higher rate of seasonal fluctuation in grasses, long-term phenological monitoring is critical when examining drought effects on the properties and dynamics of a dryland region especially in an area where cattle grazing is a critical contributor to plant stress (Havstad et al., 2006; Peters & Gibbens, 2006). Ranchers and land manager outside the JER could incorporate the low-cost, high data quality, and quick installation of phenocams to adjust cattle grazing patterns according to precipitation input and grass phenology patterns (Browning et al., 2015). This applied method would allow ranchers to practice a more sustainable land management strategy, resulting in a more productive and responsive ecosystem (Frank et al., 2013). This application might not only continue to provide a critical food source for cattle, but it may also allow the ecosystem to improve carbon storage (Frank et al., 2013; Han et al., 2016).
3. Use of alternate color space to derive phenological trends in a Chihuahuan Desert shrubland

3.1 Introduction

Since its inception in 1912, the JER has played a key role in the development of new and/or more efficient methods of data collection and analysis. Currently, phenophase observations are primarily conducted by human observers periodically recording changes on tagged plants over time (Denny, 2012). This method appears to offer high fidelity information but has disadvantages including low cost efficiency due to the physical requirement of researchers to make these observations; a risk of data inconsistency due to differences in subjectivity between observers; and low frequency of data collection due to the presence required by an observer (Booth et al., 2006; Kurc & Benton, 2010; Menzel, 2002). Although this method is tied to some challenges, it is still necessary to serve as ground control for testing newer more efficient data collection methods (Crimmins & Crimmins, 2008; Richardson et al., 2007).

One of the newer, highly preferred, and reliable methods of data collection for phenological studies is the use of time lapse photography from stationary digital cameras – or ‘phenocams’ as they are now more commonly referred (Crimmins & Crimmins, 2008; Keenan et al., 2014; Richardson et al., 2007; Toomey et al., 2015). This method (as opposed to the former method mentioned) is relatively cost efficient due to the minimal field presence required of human observers (Benton, 2009; Seefeldt & Booth, 2006). It also eliminates the issue of subjectivity and increases the frequency of data collection, allowing researchers to capture phenophase changes at finer temporal scales and from plant to landscape spatial scales (Ahrends et al., 2008; Benton, 2009; Neeser et al., 2000; Richardson et al., 2007). The introduction of phenocams has been challenged by the need for processing and analyzing large quantities of phenocam images, and
although there are established and trusted methods already set in place, there are still a myriad of
digital image analysis techniques that have yet to be explored for vegetation phenological
research.

Time lapse images for phenological studies are most commonly analyzed with imagery software
where regions of interest (ROIs) are chosen by the user and the red, green, blue (RGB) color
channels are used to assign a quantitative values to the ROIs chosen (Benton, 2009; Kercher et
al., 2003; Neeser et al., 2000). In this study, we apply this same technique of analyzing the
digital spectral signature within ROIs but we explore the potential of alternate color space for
advancing this field of research. Specifically, we focused on camera 2 at the UTEP-SEL site at
the JER (Figure 3.2), where we extracted landscape and species (creosote bush and honey
mesquite) ROIs from 2011-2015 with the PAS. We derived different color channel values for
these ROIs and conducted an inter-comparison of these values with detailed phenophase
measurements (Figure 3.5 - 3.7).

3.2 Methods

This study utilized a phenocam (Figure 3.2; Table 2.1) that was situated in a study area (Latitude:
32.581956, Longitude: -106.635025) with an elevation of 1188m and slope of ~2 degrees (Figure
3.1). This study site is maintained and operated by the University of Texas at El Paso’s Systems
Ecology Lab (UTEP-SEL) and is located within a shrubland LCT (Fig. 3.1). Time lapse images
were captured hourly from 700 to 1900 spanning 2011-2015, but only images at solar noon were
used in this study to avoid complications in digital image analysis caused by sun angle (Figure
3.3 a) (Gonzalez-Alonso, 2011; Kurc & Benton, 2010). PAS was used to process images for
landscape and species specific ROIs (Figure 3.4 a-c) that included only honey mesquite and
creosote bush plants since these were the only two species that could be clearly distinguished within the field of view (Figure 3.3 b). Images were filtered to include only those with DN values >39, which helped eliminate images that were overcast, or marred by other uncommon phenomenon that could impact results (Figure 3.3 c) (following the method of Toomey et al., 2015).

Images were processed with the color space options: RGB, HSV and L*a*b*. Most plant phenological studies - focused on northern hardwood forests and rarely expand into the dryland ecosystems - apply RGB channels and typically analyze data derived for spectral indices such as GEI or GCC (Equation 1 and 3), which have proven to be reliable and emphasize on the green channel from RGB which is especially important for plant phenological studies (Benton, 2009; Kurc & Benton, 2010; Toomey et al., 2015). However, this project explores alternate color spaces and compares them to physical phenophase observations (Figure 3.3 - 3.5) made weekly on plants at the site. A goal of this study is to determine if less investigated color channels (such as HSV and L*a*b*) in the analysis of phenocams imagery offers a greater potential for documenting phenological trends in dryland shrublands.

Weekly phenological observations (Figure 3.5 – 3.7) were made at the site from 2011-2015, which included the shrubs creosote bush and honey mesquite. Phenological observations were made using standardized status protocols reported in Denny (et al., 2014), which are based on recording the presence/absence of pre-defined criteria that is indicative of a specific phenophase, meaning if a phenophase was present on a tagged plant, it was given a “1” for that day, and if it was absent it was given a “0.” In this study, phenophase measurements from sites along two transects adjacent to the phenocam’s field of view (Table 3.1; Figure 3.1) were totaled per
transect then averaged between the two in order to establish a dataset representative of the landscape at the study site (Figure 3.3 d). The phenocam data was then aligned for comparison (by date) with the averaged phenophase observations (Figure 3.3 e).

To enhance inter-comparison of the phenophase and phenocam datasets, cluster analysis of the phenophase data was conducted with the Hierarchical Clustering option in JMP 4. Cluster analyses were conducted separately on observations collected for creosote bush and honey mesquite (Figure 3.3 f). Cut off points were chosen to better represent any major shifts in phenophases (i.e. seasons). Specifically, clusters of three and four were chosen to determine which was best suited for capturing major shifts in phenophases (Figure 3.3 g). Following cluster analysis, a one-way ANOVA in JMP 4 was used to determine which color channel derived from the landscape and species specific ROIs could best capture the phenological state represented by each cluster (Figure 3.3 h). A Tukey HSD test in JMP 4 was then run (only on significant results from the ANOVA test) to determine which clusters were significantly different from each other, thus identifying the color channels that might best capture each shift in phenology (Figure 3.3 i).
**Figure 3.1:** The USDA-ARS JER on the left with a zoomed in view of UTEP-Systems Ecology Lab (SEL) site within the eastern JER. Red dots are phenology transects monitored at the site, and the two transects circled in green are included in this study.

**Figure 3.2:** UTEP-SEL’s site with the relative field of view for the camera used to address research objective 3.
**Figure 3.3 a-i:** Flow chart of methods for Ch. 3. (a) phenocam image dataset; (b) process images with PAS; (c) filter images for any noise; (d) phenology dataset; (e) align image and phenology datasets by date; (f) run hierarchical cluster analysis on phenology data; (g) cluster groups into seasons; (h) one-way ANOVA on clusters and spectral indices from images; (i) Tukey test to determine which clusters best described by given spectral index. Steps in blue re: phenocam images only; steps in green re: phenology dataset only; and steps in orange re: both datasets together.
Figure 3.4 a-c: Field of View for cam2 within PAS. (a) The rectangle overlaid on the image is the landscape ROI; (b) the five free-hand ROIs encircle individual creosote bush plants; (c) and five free-hand ROIs encircle individual honey mesquite plants.
Table 3.1: The number of individuals for each key plant species observed at site and transect.

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<td><strong>Total individuals per site</strong></td>
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Phenophases Monitored for Creosote Bush (*Larrea Tridentata*)

A. **Breaking leaf buds** - 3.2A: Three or more breaking leaf buds are visible. For *L. tridentata* a leaf bud is considered breaking when a green leaf tip is visible at the end of the bud, but before the leaf has unfolded to expose the petiole. In Figure 10A the leaf bud is breaking from an internode on a stem.

B. **Young unfolded leaves** - 3.2B: Three or more young unfolded leaves are visible. Once the petiole is visible, the leaf is considered young and unfolded. For *L. tridentata* young leaves have a brighter green color and are slightly glossier than mature leaves. If necessary, the leaf may be bent to see if the petiole is present.

C. **Open flowers** - 3.2C: Three or more open and fresh flowers are visible. Flowers are considered open when reproductive structures are visible (e.g., pistils and stamens). Dry flowers should not count as open flowers.

D. **Full flowering** - 3.2D: *L. tridentata* is considered in full flower when 90% or more of the canopy presents open flowers.

E. **Ripe fruits** - 3.2E: Three or more ripe fruits are visible. For *L. tridentata* fruits are considered ripe when they are brown and open.

F. **Flower buds** - 3.2F: Three or more flower buds are visible and flower buds have not yet bloomed into a full-size flower.

G. **Fruits developing** - 3.2G: Three or more fruits are visible. For *L. tridentata* fruits are light green in color and have white hairs.

Figure 3.5 a-f: Key phenophases for Larrea tridentata (creosote bush): (A) breaking leaf buds; (B) young unfolded leaves; (C) open flowers; (D) full flowering; (E) ripe fruits; (F) flower buds; and (G) fruits (Denny et al., 2012). (Photographs by: Libia Gonzalez)
Figure 3.6 a-f: Key phenophases for Prosopis glandulosa (honey mesquite): (A) breaking leaf buds; (B) young unfolded leaves; (C) >25% of full leaf size; (D) >75% of full leaf size; (E) 50% leaves fallen; (F) all leaves fallen (Denny et al., 2012). (Photographs by: Libia Gonzalez) Additional phenophases monitored for honey mesquite are given in Figure 3.5.
Figure 3.7 g-l: Key phenophases for Prosopis glandulosa (honey mesquite): (G) open flowers; (H) full flowering; (I) fruits; (J) ripe fruits; (K) recent fruit drop; and (L) flower buds (Denny et al., 2012). (Photographs by: Libia Gonzalez)
3.3 Results

The hierarchical cluster analysis from JMP captured temporal shifts in the timing of key phenophases with moderate overlap in the occurrence of some phenophases. For the three cluster analysis, creosote bush was grouped by: (1) max greening, (2) flowering, and (3) fruiting (Figure 3.8). For the four cluster analysis for creosote bush, the shifts captured were: (1) green-up, (2) max greening, (3) flowering, and (4) fruiting (Figure 3.9) where green-up was only captured in 2011. For the three cluster analysis for honey mesquite the shifts captured were: (1) dormant, (2) green-up/max greening, and (3) flowering/fruiting (Figure 3.10) where fruiting/flowering was only captured in 2013-2015. Finally, the four shifts captured in the four cluster analysis for honey mesquite were: (1) senescence/dormant, (2) green-up/max greening, (3) flowering, and (4) fruiting, where 3 and 4 were only captured in 2013-2014, as shown in Figure 3.11.

There were no significant relationships from the one-way ANOVA for creosote bush spectral indices at the species level for the three-cluster classification. There were, however, strong relationships between phenocam spectral properties for creosote bush at the landscape level and the three clusters (i.e. phenophase shifts; Table 3.2). The Tukey test showed there was no color model that could strongly capture the max greening phenophase. There were, however, a few color channels that captured flowering and fruiting phenophases, but the most significant (for both phenophase shifts) was for ‘Hue’ (from the HSV color model) with a p-value of 0.0055 (Table 3.2). GEI and GCC were also able to capture flowering and fruiting with p-values of 0.0162 and 0.0246, respectively.
The four-level classification for creosote bush had various color channels capable of capturing the four phenophase shifts, supported by the Tukey HSD test (Table 3.3). ‘BlueDN’ and ‘totalRGB’ were able to capture ~75% of all phenophases - early green-up, greening, and fruiting - with the strongest p-value of <0.0001. As for the flowering phenophase, only ‘Hue’ was able to capture flowering with a p-value of 0.0279 (Table 3.3.). For this same classification, ANOVA’s at the landscape level showed that early-green up and flowering were captured by ‘Hue’ with a strong p-value of 0.005 (Table 3.4). ‘GEI’ was able to capture greening with a p-value of 0.0108 and fruiting was captured best (p-value 0.0122) by ‘BlueDN’, which was the same for the species level values mentioned above (Table 3.4).

Figure 3.8: Key creosote bush phenophase presence (%) with cluster groups (3) plotted in the background. Black line represents the clusters established from the Cluster Analysis.
Figure 3.9: Key creosote bush phenophase presence (%) with cluster groups (4) plotted in the background. Black line represents the clusters established from the Cluster Analysis.

Figure 3.10: Key honey mesquite phenophase presence (%) with cluster groups (3) plotted in the background. Black line represents the clusters established from the Cluster Analysis.

Figure 3.11: Key honey mesquite phenophase presence (%) with cluster groups (4) plotted in the background. Black line represents the clusters established from the Cluster Analysis.
Table 3.2: Difference of means for phenological observations (3 clusters) of creosote bush captured by landscape ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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Table 3.3: Difference of means for phenological observations (4 clusters) of creosote bush captured by species ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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<th>Flowering</th>
<th>Fruiting</th>
<th>p-value</th>
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Table 3.4: Difference of means for phenological observations (4 clusters) of creosote bush captured by landscape ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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<tr>
<th>Color Channel</th>
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<th>Flowering</th>
<th>Fruiting</th>
<th>p-value</th>
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<tr>
<td>test</td>
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</table>
Results for the species level honey mesquite analyses (including 3 phenophases) showed that differences in mean ‘BlueDN’ could be used to most effectively distinguish the three phenophase clusters (Table 3.5). At the landscape level comparison, no one color channel could distinguish all phenophase clusters; rather, different color channels proved to be more effective for a given phenophase cluster. For the dormant phenophase (cluster 1), there were a few color channels that captured this cluster effectively including ‘redDN’, ‘GEI’, ‘GCC’, ‘totalRGB’, ‘Hue’, ‘Value’, ‘a*’, and ‘test’ (all had $p < 0.0001$, Table 3.6). ‘L*' proved to be the best channel to capture green-up/peak productivity with a $p$-value of 0.0002. Flowering/fruiting was the best captured with ‘pctR’ ($p$-value 0.0226; Table 3.6).

Honey mesquite clusters that included 4 groups at the species level did not have a prominent color channel that captured all phenophase clusters separately (Table 3.7). Color channels that best captured senescence/dormant, green-up/growing season, and flowering were: ‘greenDN’, ‘blueDN’, ‘pctR’, ‘totalRGB’, and ‘L*’ all with a $p$-value of $<0.0001$. The only channel that captured fruiting was ‘Value’ with a $p$-value of $<0.0001$ (Table 3.7). As for the landscape level color channel values, senescence/dormant, green-up/growing season, and flowering were captured by ‘redDN’, ‘GCC’, ‘nNDVI’, and ‘Value’ which had $p$-values of 0.0001 and $<0.0001$ (Table 3.8). None of the color channels were able to capture fruiting at the landscape level (Table 3.8).
Table 3.5: Difference of means for phenological observations (3 clusters) of honey mesquite captured by species ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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Table 3.6: Difference of means for phenological observations (3 clusters) of honey mesquite captured by landscape ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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Table 3.7: Difference of means for phenological observations (4 clusters) of honey mesquite captured by species ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Rows in grey signify these did not have significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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Table 3.8: Difference of means for phenological observations (4 clusters) of honey mesquite captured by species ROI color channels. Rows in grey signify non-significant results from the one-way ANOVA. Numbers in grey represent no difference in means from the other phenophases. Numbers in red (p-value) are colored in order of significance - deep and bold red are highly significant.

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<th>Color Channel</th>
<th>Senescence/dormant</th>
<th>green-up/growing season</th>
<th>flowering</th>
<th>fruting</th>
<th>p-value</th>
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3.1 Discussion

This chapter included an exploratory analysis that assessed the utility of alternate spectral indices from time lapse images to capture key phenological states in a dryland ecosystem. No single channel or spectral index studied across RGB, HSV, or L*a*b* color space was capable of capturing all phenological states derived from the cluster analysis of phenophases. Between both shrub species included, only ‘BlueDN’ for honey mesquite was able to capture all phenological stages. Interestingly, ’BlueDN’ is not the color channel typically used to capture plant phenological development in the more commonly studied biomes such as temperate forests (Richardson et al., 2007; Toomey et al., 2015). Heterogeneity and low foliar cover, characteristic of a shrubland land cover type, might be factors affecting these more accepted methods of image analysis for plant phenology in dryland ecosystems (Huenneke et al., 2002; Kurc & Benton, 2010). As such, this study appears to have further illustrated the need for additional exploratory analyses in alternate color space for phenological studies.

There might also be an underlying issue of distance between the camera lens and the point of interest (plant) when processing the images. Considering the distance between the camera lens and plants was about 15 to 20m (Gonzalez-Alonso, 2011), and given that changes in greenness are subtle for creosote bush (Denny, 2012; Ogle & Reynolds, 2002), these factors may have made it difficult for cameras to capture those changes over time. ‘Hue’ was able to capture the timing of flowering and fruiting seen in creosote bush, which may be due to the ability of ‘Hue’ to capture more subtle changes in color than the standard RGB color model as noted in previous studies (Benton, 2009; Laliberte et al., 2007). Results from this study suggest that new approaches to dryland phenological studies employing time-lapse image processing should
consider alternate approaches to those developed for temperate deciduous and boreal ecosystems, which typically display higher foliar coverage and more regular shorter-duration annual plant phenological cycles (Broich et al., 2014).

Based on the results from this chapter, future plant phenological studies in drylands might consider correlating alternate spectral indices from time lapse images with ecosystem gross primary productivity (Kurc & Benton, 2010; Moore et al., 2016). This type of data analysis may give insight as to how dryland plant phenology contributes to land-atmosphere interactions and specifically carbon and water fluxes (Cong et al., 2013; Poulter et al., 2014; Zhang et al., 2006). Water is a limiting factor in drylands and there may be correlations between soil moisture depth and plant phenological responses during long drought periods and/or wetter years (Kurc & Benton, 2010). Dryland phenology has also shown to play a critical role in regional atmospheric carbon cycling, but monitoring these greening events has proven to be challenging with the heterogeneous landscape characteristic of dryland systems (Browning et al., 2015; Huenneke et al., 2002).
4. General Conclusions

In this study, we examined the spatiotemporal variability of plant phenology across different land cover types that are common on the JER and throughout the northern Chihuahuan Desert. Grasses seem to drive landscape phenological trends, but only in grassland LCTs; whereas, in shrubland LCTs grasses act more as contributors to landscape trends. Species cover appears to play a major role in determining which species will act as the major drivers of landscape plant phenology for any given LCT. Earlier peaks in greenness for shrubs, relative to grasses, provides evidence that winter groundwater storage and availability to deeper rooted shrubs likely plays a critical control in determining the difference in the timing of greening captured by cameras. Although grass responses are sensitive to irregular precipitation events they still act as key contributors to overall landscape phenology trends as well as a main source of energy for large mammals (cattle) and income for ranchers whom own these cattle. Time lapse cameras could be easily implemented into cattle grazing methods in order to lower the detrimental effects of overgrazing previously noted across the JER.

This study also explored the capability of capturing key plant phenophase shifts with the use of alternate spectral indices derived from time lapse image analysis. While there are many studies readily available from different ecosystems, phenological studies in dryland ecosystems remain scant. The patchy heterogeneous landscape of drylands cannot compare to that of the lush boreal or dense rainforest ecosystems where phenocam analysis methods have been developed and applied. This study has shown that non-conventional approaches using alternate color space might offer a greater efficacy for capturing phenological events that are not easily discerned in RGB color space.
5. Suggestions for future work

This study sets the tone for many studies that can build from the results found here. One idea is determining which factors most heavily influence (drive) spatiotemporal variability in dryland plant phenology. Precipitation is a limiting factor in these environments, but there are other factors such as temperature, soil moisture, and carbon fluxes that surely play a role in phenological observations. Correlations can be made between the timing of major shifts in change (i.e. onset greening, maximal greening, and onset senescence) and the aforementioned drivers. While there are strong ties to precipitation and grass phenology, there may be another that more heavily drives shrub phenology. This may elucidate just how dynamic and complex these dryland plants are and what resources they rely on most for growth.

Scaling is an issue in all ecosystems, but fine-scale studies are not relatively studied in dryland environments. It is known that plant phenology in drylands contributes significantly to regional and global scale carbon cycling through photosynthesis. Linking leaf-level physiological measurements to plant level phenology can help elucidate how these two different scale measurements are related and how that can be interpreted in future studies through time lapse image analysis methods. This can also be applied to even broader scale measurements such as satellite imagery. This may prove helpful by improving data analysis methods in pre-existing cross scale analysis issues in patchy low plant cover environments that is typical of a dryland ecosystem.

Another interesting study might be to redo Ch.3, but with images at a smaller scale. The distance from the camera lens to the point of interest (individual plants in the field of view) may have played a role in capturing subtle changes in greenness common for dryland shrubs.
closer range approach will provide allow color signatures from images to better capture phenological measurements. This, again, is another example of a scaling issue and can elucidate the strong need to address cross scale analysis especially in heterogeneous landscapes which makes capturing plant phenology with images even more difficult.
6. References


Moore, Caitlin E; Keenan, Trevor F; Duursma, Remko A; Albert I J M van Dijk; Hutley, L. B. (2016). Reviews and syntheses: Australian vegetation phenology: new insights from satellite remote sensing
and digital repeat photography, 5085–5102.


7. Curriculum Vitae

Naomi Robin Luna completed her Bachelor’s Degree at The University of Texas at El Paso in 2013. During her last two years she worked as a Research Assistant at UTEP where she collaborated in several projects related to dryland ecosystems and image analysis for monitoring plant productivity in these harsh environments. In 2013, she was awarded the EPA Air Quality Internship at UTEP. While working in the lab, Robin found her passion for research in dryland ecosystems and decided to enter the Master’s program in Environmental Science at UTEP under the direction of Dr. Craig E. Tweedie. Her thesis entitled “Spatiotemporal variability in plant phenology in drylands: a case study from the northern Chihuahuan Desert” investigates the variability of plant productivity between different plant communities across a dryland ecosystem via spectral signatures from time lapse imagery; along with this it explores new methods for analyzing these time lapse images.

During her studies, Robin worked as a research assistant position, as well as one semester as a teaching assistant giving her the skills to communicate science to other students. Robin participated in a program called TIERA, working as a mentor, helping students explore the possibilities beyond academia through research. She has presented at several national conferences many of them awarded with travel scholarship. Ms. Luna’s research interests focus on the effects of climate change on plant productivity and its effects on this harsh environment.