Spring 1-24-2018

# Impact of Drought on Land Cover Changes in Diné Bikéyah – A Study through Remote Sensing

Anjanette A.J. Hawk
*University of New Mexico - Main Campus*

Recommended Citation

Hawk, Anjanette A.J.. "Impact of Drought on Land Cover Changes in Diné Bikéyah – A Study through Remote Sensing." (2018). https://digitalrepository.unm.edu/geog_etds/37

Anjanette A. J. Hawk
*Candidate*

Geography and Environmental Studies
*Department*

This thesis is approved, and it is acceptable in quality and form for publication:

*Approved by the Thesis Committee:*

Chris Duvall , Chairperson

Karl Benedict

Caitlin L. Lippitt

# IMPACT OF DROUGHT ON LAND COVER CHANGES IN DINÉ BIKÉYAH – A STUDY THROUGH REMOTE SENSING

**by**

**ANJANETTE A. J. HAWK**

**B.S. Anthropology, University of New Mexico**
**2012**

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

**Master of Science**
Geography

The University of New Mexico
Albuquerque, New Mexico

**May 2018**

# ACKNOWLEDGMENTS

I acknowledge Chris Duvall, my advisor, my chair, for encouraging me throughout the months of revisions it took to complete this research. His guidance and professionalism will remain with me as I continue my future goals and endeavors.

I also thank my committee members, Dr. Karl Benedict, and Dr. Caitlin Lippitt, for their valuable recommendations, and knowledge pertaining to this research. Their expertise will help broaden my professional development.

An appreciation to my colleague and friend, Su Zhang for his support and knowledge in assisting with weeks of analyses.

Thank you to my grandparents, Dennis and Mary Hardy, their perpetual love, encouragement, and prayers. Ahéhee’ Shí Cheii dóó Shí Másání, Ayóó ánííníshí.

To my boyfriend, Theron for all his support, reassurances, and love throughout this journey, thank you for your love and dedication.

And, finally, my family, friends, and co-workers for their support and encouragement throughout this study.

# Impact of Drought on Land Cover Changes in Diné Bikéyah – A Study through Remote Sensing

**By**

**Anjanette A. J. Hawk**

**B.S. Anthropology, University of New Mexico, 2012**

**M.S. Geography, University of New Mexico, 2018**

## Abstract

This study identifies land cover changes associated with a ten-year drought period and discusses the importance of vegetation change in Diné Bikéyah, a semi-arid land located in a remote part of the southwestern United States (US). This study concludes that drought produced slight changes in vegetation within a 540 km$^2$ study area in the Tselani-Cottonwood Chapter (TCC) in Diné Bikéyah. The data for this study consist of three Landsat images for the years 1998, 2002, and 2009. The methods used to analyze these Landsat images included image pre-processing, calculation of normalized difference vegetation index (NDVI) images, and supervised (maximum likelihood) classification of land cover. The classification analysis yielded five land-cover categories; land-cover change was assessed using standard change-detection techniques, followed by accuracy assessment of the results. Land-cover change was minimal over the ten-year study period in the TCC, which suggests that vegetation in the study area is resilient to drought and livestock grazing. Identifying land-cover change provides insight on the impact of a drought in Diné Bikéyah. Given the importance of vegetation in Diné livelihoods, and the limited knowledge of land-cover change associated with drought and other climate events, analysis of land-cover change using remote sensing offers the ability to understand how Diné people and livestock might contribute to land-cover change in addition to developing sustainable livestock management strategies.

# Contents

## List of figures

## List of Tables

# Chapter 1 Introduction

## 1.0 Introduction

Drought is a natural hazard that occurs every year across different portions of the US. Droughts are usually defined as a reduction in precipitation received over an extended period, such as a season, a year, or longer (Mishra & Singh, 2010). Droughts vary in three essential characteristics: intensity, duration, and spatial coverage (Wilhite, 2000).

Droughts impact surface, groundwater resources and land-cover, thus can affect economic and social activities through reduced water supply, crop failure, reduced range productivity, and diminished vegetation (Mishra & Singh, 2010). As climate change is predicted to increase in the southwest United States (Pachauri et al., 2014), monitoring land-cover changes in the area is important. Studies such as Keener (2013) described the warmest and the fourth driest period in the Southwest from 2001-2010. Annual average temperatures for 2001–2010 were 1.4°F (0.8°C) warmer than the average temperatures from 1901–2000. Keener (2013) also describes the intensity of warming as it relates to changes in temperatures during spring and summer, and at particular times of the day. Another study by Redsteer et al., (2012) identified Diné Bikéyah (the Navajo homeland) as having experienced a drought that officially lasted from 1999-2009. Diné (Navajo people) continue to recover from this drought, and are challenged by an increasingly dry climate. Increasing temperatures and further deterioration of rangeland are trends we can expect to continue with climate change in Diné Bikéyah (Redsteer et al., 2012).

The livelihoods of many Diné are subsistence-oriented and are inextricably tied to, and depend on, land-cover conditions and water supplies. Diné livelihoods have many adaptations to drought. Diné presently living on Diné Bikéyah are unique in American society as their traditional lifestyle requires knowledge of the ecosystem (Redsteer et al., 2012), knowledge that was passed down from generation to generation through oral traditions.

Many Diné residents, especially the elderly, have relied on raising livestock gathering various plants as an important part of their livelihood or as a supplement to food supplies (Bailey & Bailey, 1986; Kuznar, 2001; Mayes et al., 1989; Redsteer et al., 2012; Weisiger, 2007; Weisiger & Cronon, 2009). Over half of the Diné residents live in housing without indoor plumbing or electricity. Homes without plumbing are dependent on hauling water from nearby sources, and use other water sources intended for livestock rather than domestic use (Kuznar, 2001; Redsteer et al., 2012). Many of the water supplies on Diné Bikéyah come from shallow alluvial aquifers.

In Diné Bikéyah, it is important to understand possible land-cover changes caused by drought. Remote sensing data present several advantages for understanding land-cover change, including when these changes are associated with drought impacts. In this research, remote sensing techniques for land-cover change analyses are applied to a study area in the central Diné Bikéyah during a ten-year drought period (1999-2009).

This thesis aims to identify land cover change from 1998 to 2009. This research aims to: 1) Identify changes among five broad land cover classes (dense shrub, dense grassland, sparse shrub, sparse grassland, and barren land), and 2) Quantify how much land cover changed. The results are interpreted to understand the comparative accuracy of two data sources, and understand how drought-related land-cover change might impact Diné livelihoods.

The paper is organized as follows. After a brief introduction and literature review in Chapter 1, Chapter 2 describes the methods used to identify land cover changes in this study, the results of which are presented in Chapter 3. Chapter 4 provides a discussion of the results.

## 1.1 Literature Review

Land cover change is an important elements of global environmental change processes (Dewidar, 2004). The detection and monitoring of change using satellite image data has been a topic of interest in remote sensing. Many studies (Akbari et al., 2006; Banskota et al., 2014; Cohen & Goward, 2004; Mei et al., 2015) in remote sensing use Landsat imagery, which is a cost-effective source of imagery with 30-meter spatial resolution, a temporal repeat frequency of 16 days, and an historical archive (40+ years) of remotely sensed data (Holden & Woodcock, 2016; Roy et al., 2016). By utilizing Landsat archival satellite data, several types of remote sensing techniques such as supervised classification, post-classification change detection, can be used to characterize land-cover change on a landscape. Post-classification change detection quantifies land cover change by comparing independently produced classified images from different dates. Thus, Landsat imagery is widely used for land cover monitoring and change detection analyses (Mei et al., 2015). For example, study by Bakr et al., (2010) monitors land cover changes using multi-temporal remotely-sensed data that provides an effective and accurate assessment of human impact on the environment. Another study by Schulz, et al., (2010) investigates land cover changes in Central Chile using multi-temporal satellite imagery taken in 1975, 1985, 1999 and 2008. Their results show major trends in reduction of dryland forest and conversion of shrubland to intensive land uses such as farmland (Schulz et al., 2010).

## 1.2 Methods Used To Identify Land Cover Change - Remote Sensing

Landsat imagery has several advantages: 1) with more than 40+ years of archival imagery, Landsat offers the longest-running time series of systematically collected remote sensing data (Banskota et al., 2014; Cohen & Goward, 2004; Holden & Woodcock, 2016; Roy et al., 2016). 2) the spatial resolution of the data can classify characteristics of land cover changes with moderately high detail and 3), Landsat data has freely available to the public and advances in image processing software and computer processing power make it possible to acquire and analyze large volumes of information.

### 1.2.1 Landsat imagery and vegetation

Landsat was the first satellite system deployed to collect data on land cover (Cohen & Goward, 2004; Lauer, Morain, & Salomonson, 1997). Landsat-5 TM launched in 1993 was discontinued in 2013, Landsat-7 ETM+ launched in 1999 is currently operational and providing data (Cohen & Goward, 2004; Lauer et al., 1997; Markham, Storey, Williams, & Irons, 2004). Landsat 8 is the newly launched satellite continuing the long and extremely important record of Earth observation from the Landsat program. Landsat TM is a seven-spectral-band sensor with eight-bit radiometry, which also includes a thermal band that has a 120-meter instantaneous field of view (IFOV) and six reflective bands with a 30-meter IFOV. Landsat ETM+ includes a 15-meter IFOV panchromatic band, six 30-meter reflective band, and a 60-meter IFOV thermal-infrared band. The Landsat system has been used for terrestrial monitoring and for evaluating regional to global land dynamics.

Photosynthetically active vegetation produces a unique solar reflectance spectrum that can be captured by multispectral sensors. Photosynthetic vegetation has low reflectance in visible wavelengths and high reflectance in near-infrared (NIR) wavelengths.  Horler and Ahern (1986) conducted the first detailed analysis of forestry information using Landsat TM data in western Ontario and Arkansas. They revealed that the short wavelength infrared (SWIR) bands contained more information about conifer and hardwood forests than the other bands. Subsequently, Cohen and Goward (2004) found that TM SWIR was an important spectral band for estimating forest volume and LAI in conifer forests (e.g. Eklundh, harrie, & Kuusk, 2001).

It is recommended that remote sensing imagery for land cover characterization be selected before the winter period to capture important phenological events and with clear sky conditions to avoid uncertainties of inter-annual variability (Lunetta & Elvidge, 1998). Understanding phenological events in the environment is essential for timing image collection in order to maximize separability between different types of vegetation. In semi-arid New Mexico, a study by Weiss et al., (2004) calculated six distinct vegetation communities in monsoon season (June September) precipitation and non-monsoon (October May) precipitation by using NDVI and meteorological variables. Landsat (e.g. TM and ETM+) provides the spectral and temporal resolution needed to perform most image-based analysis at a moderate (30 x 30 m) spatial resolution. Additionally, Landsat offers the potential of generating detailed vegetation classification to understand the effects of drought in specific land cover classes, even though the data-set offers relatively low temporal resolution (a 16 day repeat cycle yielding about two images per month). Vanderpost et al., (2011) used Landsat imagery to assess the long-term conditions of rangeland in semi-arid areas of Botswana and, by calculating vegetation indices, found significant degradation in vegetation corresponding to the droughts between 1984 to 2000. On the other hand, Fadhil (2011) used only two Landsat images from consecutive years to calculate five vegetation and soil/vegetation moisture indices in the Iraqi Kurdistan region. However, this approach lacked the continuity of time series analysis and was unable to anticipate the evolution of drought (Sierra-Soler et al., 2016).

### 1.2.2 Land cover change

Land cover is the physical material at the surface of the earth. Land cover includes materials such as vegetation, grass, soil, asphalt, trees, bare ground, and water. Various image-processing methods allow specific land cover materials to be identified. For instance, normalized difference vegetation index (NDVI) allows for the transformation of multispectral data to represent vegetation abundance and the amount of green vegetation present in a given pixel (Mei et al., 2015). Other methods can be used to quantify changes between land-cover classes. For instance, post-classification analysis can detect land cover changes by comparing independently produced classifications of images from different dates (Lunetta & Elvidge, 1998; Singh, 1989).

There are numerous satellite systems currently collecting data on land cover (i.e. SPOT, MODIS, or LANDSAT 8). Abd El-Kawy et al., (2011) consider the Landsat program as unique because it provides continuous historical record of imagery. Numerous studies have used Landsat data to identify land use and land cover changes, many of which focused on semi-arid regions (e.g. Abd El-Kawy et al., 2011; Lu et al., 2004; Shalaby & Tateishi, 2007; Zhou, Li, & Chen, 2011). For example, Shalaby and Tateishi (2007) identified land cover changes in the coastal zone of Egypt from 1987 to 2001. Their findings demonstrated extensive changes from agricultural lands to tourist development, with the area of natural vegetation decreasing substantially.

### 1.2.3 Vegetation Analysis in Remote Sensing

Yang, Yang, and Merchant (1997) define Normalized Difference Vegetation Index (NDVI) as the ratio of the difference between the reflectance in the near-infrared and red wavelengths. Studies using remote sensing that addresses phenology will typically start with gathering data from satellite sensors to measure wavelengths of light absorbed and reflected by green plants. There are certain pigments in plants (leaves) that strongly absorb wavelengths of visible (red) light. The plants (leaves) strongly reflect wavelengths of near-infrared light (visible to the human eye). As seasons change, so do plant canopy (e.g. from early spring growth to late-season maturity and senescence), and reflectance properties. NDVI is widely used as a vegetation index which allows scholars to transform multispectral data into a single image band representing vegetation distribution and the amount of green vegetation present in a location (Mei et al., 2015).

There are many examples of NDVI used in studies of land cover. Adamo and Crews-Meyer (2006) used unsupervised classification and change detection matrices. In their findings, vegetation in Argentina in 2001 had decreased by 39% since 1973, likely associated with the variations in moisture availability. Scholars such as Lin and Brunsell (2013) examined NDVI and precipitation to address potential impacts of drought in the Kansas River Basin. Another study in the north-east of the Iberian Peninsula between 1987 and 2000 by Vicente-Serrano (2007) reveals that the effect of drought on vegetation varies noticeably between areas, a pattern that is determined by land-cover types.

In the most arid areas, where vegetation cover is low, the inter-annual variability of vegetation activity is determined by the amount of precipitation. Bradley and O'Sullivan (2011) used remote sensing to identify landscape-scale changes with Landsat TM, using NDVI as a proxy for community greenness. In addition, the authors identified grazing allotments, and identified recent landscape-scale changes including reduced grazing intensity and reduced grazing in riparian zones. Also, Bakr et al., (2010) utilized five Landsat images to monitor land cover changes from 1984 to 2008 in Egypt. Their study area in Egypt was 100% barren land that changed to 79% agricultural land between 1984 to 1990. They mention that during the 1900s there was a reclamation process that produced changes in land cover. This process provided an effective and accurate evaluation of human impact on the environment. Their NDVI results showed that the vegetated areas increased after the reclamation process.

Once vegetation classes have been identified and located on a landscape, satellite images can be analyzed to detect land cover change. Change detection is defined as the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh, 1989), and by controlling variance caused by variables that are not of interest and measuring changes caused by variables of interest (Lu et al., 2004). For successful change detection, satellite images should be acquired by the same sensor, using the same resolution and at the same acquisition time during the year (Mei et al., 2015). One of the major applications of remotely sensed data obtained from Earth-orbiting satellites is change detection because of repetitive coverage at short intervals and consistent image quality (Anderson, 1976). Change detection is useful in diverse applications (Singh, 1989) such as monitoring of shifting cultivation, assessment of deforestation, study of changes in vegetation phenology, seasonal changes in pasture production, and other environmental changes..

There are many examples of supervised classification used to study land-cover change. Alrababah and Alhamad (2006) used Landsat Enhanced Thematic Mapper Plus (ETM+) imagery in Northwestern Jordan to characterize land use and land cover. They applied supervised and unsupervised classification schemes to identify land cover. Their results indicated that Landsat ETM+ images are effective in classifying heterogeneous Mediterranean landscapes with an accuracy of up to 83%. Lang et al., (2008) conducted classification experiments with Landsat Thematic Mapper (TM) image and ETM+ image by applying a data-assisted labeling approach (DALA) process which includes unsupervised classification, development of land use and land cover maps, and accuracy assessment. Their study suggested that DALA was effective in making unsupervised classification processes more objective, automatic, and accurate.

The Post-classification Component (PCC) method is recognized as the most accurate change detection technique, which detects land cover changes by comparing independently produced classifications of images from different dates (Lunetta & Elvidge, 1998; Singh, 1989). A study by Mas (1999) tested six change detection procedures for areas in Mexico. This study pointed out that the post-classification appeared to be the most accurate procedure and presented the different nature of changes in land cover. The PCC method minimizes the problems associated with multi-temporal images recorded under different atmospheric and environmental conditions. Data from different dates are separately classified, and reflectance data from multi-dates do not require adjustment for comparability (Coppin et al., 2004). The PCC method has the advantage of indicating the nature of change (Abd El-Kawy et al., 2011). Post-classification is defined as an approach to provide “from-to” change information, the kind of landscape transformations that have occurred, and calculate and map these changes (Yuan et al., 2005). This approach is a common method used for change detection (Mei et al., 2015).

Some techniques such as image differencing can only provide change and non-change information, while some techniques including post-classification comparison can provide a matrix of change (Lu et al., 2004). An error (confusion) matrix is the most common method of performing classification accuracy assessment for any application of remote sensing. To perform a proper accuracy assessment, the number of generated random points should total 250 or more (ERDAS, 2007). Foody (2002) defines the term accuracy as a construct to express the degree of ‘correctness’ of a map or classification. A map derived from a classification cannot be considered accurate unless it provides an unbiased representation of land cover of the area it portrays. Loveland et al., (1999) and Foody (2002) argue that a lack of standards in accuracy assessment is a key problem in classifying land cover. Foody (2002) concludes that the most promising accuracy assessment approach is the error (confusion) matrix.

The confusion matrix provides the basis to describe classification accuracy and characterize error and may help to refine classifications. In addition, Foody (2002) states that in studies of land cover change based on temporal sequence with remote sensing imagery, misregistration errors can occur, significantly mask change, and limit the value of remote sensing for monitoring land cover dynamics. The problem here is that the confusion matrix may contain errors due to misregistration, and thematic mislabeling will complicate the interpretation. Thus far, and in most of the literature, it has been assumed that the ground reference data used in the assessment of classification accuracy are themselves an accurate representation of reality (Foody, 2002). Despite this, Congalton (1991) and Foody (2002) argue that ground data are just another classification that may contain error. These errors may be due to inaccurate class labels but may include other errors such as mis-location.

### 1.2.4 Remote sensing and Indigenous Livelihoods

Remote-sensing studies have contributed to participatory assessment of natural resource conditions and planning for natural resource management in areas used for indigenous livelihoods. By bringing together indigenous knowledge and advanced remote-sensing techniques, geographers can evaluate theories of land-cover change and land-use ecology thereby understand how these ideas affect indigenous peoples. In addition, Fairhead, Leach, and Millimouno (2011), using remote-sensing analyses while working in semi-arid West Africa, strongly suggests that we need to depend on indigenous knowledge and tradition before jumping to "scientific" assumptions and making impulsive and perhaps counterproductive policy decisions.

There has been a limited amount of research using remote sensing to understand land cover and indigenous livelihoods in the Southwestern US, even though this region is where the largest reservation and rural Native American population exist. Most research has been done in the arctic, and in low-latitude areas, and little has been done in the continental US. Remote Sensing has been used to identify vegetation types and land-use areas that are related to indigenous livelihoods in these areas such as west Africa (Fairhead et al., 2011). Remote sensing is important to identify and describe patterns of land-cover distribution and change, specifically to understand relationships between indigenous livelihoods and environmental change (Fairhead et al., 2011). Remote sensing has been useful in challenging dominant understandings of land-use change, which have commonly been based on foreign biases against indigenous livelihoods (Fairhead et al., 2011). This research is relevant to understanding assumptions in the management approach of livestock reduction. Specifically, livestock reduction is based on the idea that indigenous livestock management in Diné Bikeyah is damaging to vegetation conditions, especially during periods of drought. However, this relationship between land cover, drought, and livestock numbers has not been clearly shown in Diné Bikéyah.

An important aspect of research on remote sensing and indigenous livelihoods is to increase participatory assessment of environmental conditions and change. This research provides a feasibility study showing it is possible to identify land-use conditions and change in Diné Bikéyah, using remote-sensing data and analyses. This is a necessary basis for further studies of livelihoods in Diné Bikéyah, and a key step in developing the capacity of Diné scientists and natural resource managers to do future research on land-use ecology and indigenous livelihoods. Currently, the Navajo Nation tribal government utilizes Geographic Information Systems (GIS) to design transportation projects and evaluate traffic patterns; to locate animal habitats; to map land ownership; to locate public utilities, including water lines, electric lines and sewer lines; and to locate water resources, including wells, ponds, lakes, streams, rivers, drainages, and watering holes. However, the tribal government does not use remote sensing methods to assess land-cover conditions and changes or grazing activities.

## 1.3 Physical Geography of Drought In Semi-Arid Areas

### 1.3.1 Drought definitions

There is no universal definition of drought because of geographic differences in hydro-meteorological variables, socioeconomic factors and the nature of water demands in different regions (Mishra & Singh, 2010). Droughts occur in all climatic zones, such as high and low rainfall areas. Droughts are commonly defined as a reduction in precipitation received over an extended period, such as a season, a year, or more (Mishra & Singh, 2010). Many scholars define drought differently. For example, Yevjevich (1967) stated diverse drought definitions are one of the principal obstacles to investigations of droughts. Wilhite and Glantz (1985) recognize both conceptual and operational definitions. As an example, conceptual definitions stated in relative terms (e.g., a drought is a long, dry period). On the other hand, operational definitions attempt to identify the onset, severity, and termination of drought periods. In general, Mishra and Singh (2010) give an example of an operational definition that can be used to analyze drought frequency, severity, and duration for a given return period. Drought definitions also differ depending on the variable (such as Meteorological, hydrological, agricultural, or socio-economic) used to describe the drought.

### 1.3.2 Drought Indices

There are several drought indices which have been derived in recent decades (Mishra & Singh, 2010). A drought index is a prime variable for assessing the effect of a drought and defining different drought parameters (e.g. intensity, duration, severity and spatial extent). For example, Mishra and Singh (2010) state that a drought variable should be able to quantify the drought for differential time scales for which a long time series is essential, such as yearly or monthly.

Although the yearly time scale is too long, for some application it can be used to gather information on the regional behavior of droughts. The monthly time scale is more appropriate for monitoring the effects of a drought in situations related to agriculture, water supply and ground water abstractions (Panu & Sharma, 2002). A time series of drought indices provides a framework for assessing drought factors of interest. The most commonly used index is the Palmer Drought Severity Index (PDSI) develop by W.C. Palmer in 1965 (Figure 3). Palmer (1965) recognized a need for a tool to better monitor drought intensity, duration, and spatial extent, and as an outcome introduced the PDSI. PDSI is widely applied for quantification of droughts (Dai, Trenberth, & Qian, 2004; Lloyd-Hughes & Saunders, 2002; Szinell, Bussay, & Szentimrey, 1998; van der Schrier et al., 2007). The PDSI is an index of meteorological drought. PDSI values are calculated from precipitation and temperature, as well as water capacity of soil for different periods. PDSI is standardized for different regions and periods. PDSI is a common drought assessment tool for large areas with different climates. If PDSI values are negative (or positive), they indicate dry (or wet) periods, while values around zero represent near-average water balance.

The United States Department of Agriculture (USDA), National Oceanic and Atmospheric (NOAA), and National Drought Mitigation Center derive a weekly drought monitor (DM) that incorporates climatic data and professional input from all levels (Svoboda et al., 2002) (http://drought.unl.edu/). The DM product is scaled to five drought categories. The categories consist of D0 (abnormally dry area) to D4 (exceptional drought event) and labels indicating the sectors being impacted by droughts (A for agricultural impacts, W for hydrological impacts, and F to indicate risk of wildfires). The Drought monitor is a consensus product reflected by best judgement of many experts based on various indicators.

### 1.3.3 Droughts as Natural hazards

Obasi (1994) and Wilhite (2000) both agree that the most important of all natural hazards is drought when measured in terms of the number of people affected. As a natural hazard, droughts differ from other natural hazards in a number of ways. First, the beginning and the end of a drought are difficult to determine and the impacts of a drought increase slowly. In addition, drought impacts often accumulate over time and may linger for years after termination. Tannehill (1949) and more Wilhite, Sivakumar, and Pulwarty (2014) state that a drought is often referred to as a creeping phenomenon. Wilhite, Sivakumar, and Pulwarty (2014) also state that the difficulty in defining drought leads to confusion. Finally, the impacts from drought are non-structural and spread over large geographical areas.

Drought is considered (Mishra & Singh, 2010; Wilhite et al., 2014) to be the most complex but least understood of all natural hazards, affecting more people than any other hazard (Hagman, 1984). Mishra and Singh (2010) argue that droughts have a complex web of impacts over various sectors of the society, including economy and may reach well beyond the geographic area experiencing a drought. Kogan (1997) points out that drought is a widespread phenomenon, with about half of the earth's surface vulnerable to them. According to the Intergovernmental Panel on Climate Change (IPCC) report, Hosseinizadeh et al., (2015) argued that climate change is the greatest threats facing the world today and future generations, and that by the end of the 21st century, global coverage surface temperatures will increase between 1.5 to 2˚C by the end of the 21st century comparative to the period from 1850 to 1900 (IPCC 2013). Historical and paleoclimatic observations indicate recurring periods of drought in the southwest (Weiss, Castro, & Overpeck, 2009), which means that understanding land-cover changes associated with drought is important for understanding potential impacts of drought.

Weisiger (2007) reported evidence of significant droughts in the 1100s, 1250s, and the late nineteenth century. The 1870s and 1880s were extremely dry according to tree-ring data, and in 1899 to 1904, Diné Bikéyah received little snow and rainfall for some years. Weiss et al., (2009) stated that the most notable southwest droughts are those that occurred in the late 1890s to early 1900s, the 1950s, and most recently the early 2000s. Therefore, climate change may result in extreme events such as drought (Wilhite et al., 2014). Hosseinizadeh et al., (2015) observed change in climate that alter the frequency and duration of drought especially in semi-arid environments. As an example, Weiss, Castro, and Overpeck, (2009) note that southwest US droughts are conspicuous over the instrumental record of the past century. Most noticeable are the droughts of the late 1890s and early 1900s, the drought of the 1950s, and the recent (possibly still ongoing) drought of the early 2000s (Seager, 2007).

Among many natural hazards in the 20th century, droughts have had the greatest detrimental impact to human and economic losses  (Bruce, 1994; Obasi, 1994). In prior years across all continents, large scale intensive droughts have been observed (Le Comte, 1994, 1995). Mishra and Singh (2010) state that an increase in economic and social costs has led to growing attention to droughts. Amongst recent studies on understanding drought impacts, Andreadis and Lettenmaier (2006), have observed that droughts have become shorter, less frequent, and cover a smaller portion of the US over the last century. Except in the southwest US and parts of the interior of the West, increased precipitation, increased temperature has led drought characteristics that are opposite to the rest of the country especially in cases of drought duration and severity have increased (Andreadis & Lettenmaier, 2006). During the last two decades, the impacts of droughts increased significantly in the US with increased severity (Mishra & Singh, 2010). Folger, Cody, and Carter (2012) and Cook et al., (2004) state that weekly estimates of drought conditions since 2000 have shown that extreme droughts have affected some part of the country nearly every year. In many cases, droughts have had heavy economic impacts. For example, the impact of the 1988 drought on the US economy was estimated at $40 billion. Ross and Lott (2000) investigated the years 1980 to 2003, in the United States. They found that droughts and associated heat waves accounted for 10 of the 58 weather-related disasters. Further, in Western Canada, during the past two centuries, at least 40 long-duration droughts occurred (Mishra & Singh, 2010). Within the 20th century, major droughts occurred in Eastern Canada, though these are generally shorter, smaller in area, less frequent, and less intense than droughts in the western US (Mishra & Singh, 2010). Nonetheless, eastern US droughts have significant, measurable impacts, which illustrates the overall importance of understanding the environmental impacts of drought in any location. For instance, Mitchell (2002) states that in 2001, following a period of drought, levels of the Great Lakes plunged to their lowest levels in more than 30 years, with Lake Superior and Lake Huron displaying near record low water levels.

Droughts influence both surface and groundwater resources that can lead to reduced water supply, deteriorated water quality, crop failure, and reduced range productivity (Meyer et al., 1992). Timing, such as season of occurrence, delays in rainy season, occurrence of rains in relation to crop growth stages and the effectiveness of the rains, is a significant determinant of drought impact. Crop or forage yields may be normal or above normal during a drought if rainfall is timely (i.e., coinciding with critical phenological stages) (Wilhite, 2000). Accordingly, having corresponding meteorological data is important while detecting land cover changes. These land-cover changes will have spatially and temporally varying environmental impacts, such as altering local water cycling in different regions.

In addition, drought periods can trigger processes of land degradation (Schlesinger et al., 1990). Adamo and Crews-Meyer (2006) define land degradation as the reduction or loss of the biological or economic productivity and complexity of agricultural land. Vicente-Serrano (2007) states that drought periods can result in significant environmental losses and can contribute to land degradation.

Land degradation has been understood not simply as a consequence of drought, but also as a consequence of land-management decisions. In many cases, livestock herding and grazing have been suggested as factors that contribute to land degradation. For example, a study conducted in China by Gao and Liu (2010) determined the causes of land degradation by detecting a long-term record of land cover change. The research entailed mapping satellite imagery in 1992 and 2002 and concluded that the area was subject to land degradation in the form of desertification. This study proposed reductions in grazing and farming to lessen the degradation (Gao & Liu, 2010). Specifically, the overgrazed areas should be sealed off from grazing and banned temporarily during growing seasons to give the grass a chance to regenerate (Gao & Liu, 2010). In contrast, Brown and McDonald (1995) state that the best way to preserve the open spaces, arid eco-systems, and diverse biota of the Southwest is to keep rural people on the land. This approach can help organize livestock ranching in ways that are ecologically and economically sustainable. In the West, ranching is economically dependent on seasonal grazing on public lands, and it is in the interest of ranchers, government managers, and the public that these lands be managed so degradation is stopped and areas of damaged ecosystems be restored (Brown & McDonald, 1995).

### 1.3.4 Vegetation response

Vegetation response to drought is complex because ecosystems change in structure and function over time. Several key aspects of this complexity may be noted. First, there may be lag times between a drought event (or other disturbance) and observed vegetation changes. Second, there is spatial variability in how vegetation responds, based on soil factors and other forms of disturbance (such as livestock grazing) (Floyd, et al., 2003). Third, there are differences in responses between species, based on their susceptibility to water shortage as well as other forms of disturbance (Pickett & Cadenasso, 2005). Finally, there are differences between landscapes, so that studies done in one landscape may not accurately predict changes in another landscape.

It is important to realize that the vegetation cover of land surfaces influences the surrounding atmosphere and hence local climate (Maarel, 2005). The abundance and activity of different species changes with season and through time since disturbance, as well as the number of species present and flows of energy and vary within ecosystems (Maarel, 2005). The idea of ecological succession described by Clements (cited in Maarel, 2005) may not accurately describe ecosystem change because of various sources of complexity. Pickett and Cadenasso (2005) show that different ecosystem properties can change at different rates, and some ecosystems display rather slight changes upon disturbance. These ecosystems are described as resilient to disturbance. Resilience exists because of ecological processes that produce self-regulation, an important ecosystem property that may support long-term and sometimes heavy land use without suffering destructive impacts (Huntley & Baxter, 2005; Maarel, 2005).

A complication to the classification of vegetation types that Pickett and Cadenasso (2005) identify is the fact that vegetation is not stable and unchanging. They understand the concept of disturbance as “an event that alters the structure of vegetation or the substrate vegetation is growing on” (Pickett & Cadenasso, 2005). Therefore, the intensity of an ecological disturbance depends upon how many layers of vegetation are removed, or how deeply the substrate is stirred or buried (Pickett & Cadenasso, 2005). Different disturbances have different effects on the resources available for colonizing plants. For instance, Dick-Peddie, Moir, and Spellenberg, (2000), summarizing knowledge of vegetation in New Mexico, found that under intensive grazing, shrubs and forbs replace grasses. In addition, they reported that Black Grama grass suffers more from drought than snakeweed. Although when insect damage is added, Snakeweed suffer more than Black Grama during a dry period. These complex interactions within vegetation communities produce land-cover change that may be detected in remotely sensed images, such as through a change from grassland to shrubland.

Schwinning and Sala (2004) report that relatively small rainfall events between 2 and 5 mm are the most common rainfall events in semiarid ecosystems. In addition, Lin and Brunsell (2013) argue precipitation is a primary control of vegetation dynamics in observable ecosystem responses. Another study by Beatley (1974) states that critical autumn rains are linked to Mojave and Transition desert systems in which some component (shrubs and certain herbaceous perennials) take advantage of rains in other seasons. Beatley (1974) notes that shrubs are dominant plants, and that seedlings may appear following the autumn rain or in the season following heavy early spring rains. In contrast, herbaceous perennials or perennial grasses grow following late summer or early autumn (August – September) rain, resulting in herbaceous perennials that appear to follow the pattern of shrub growth. Overall, Beatley (1974) reports that the differences in rainfall over the land surface may have large consequences to the local success of the biological season. In addition, Beatley (1974, p. 863) concludes that "whether seasonal success is to be regional or local, and the extent to which the producer-consumer relationships will proceed, is therefore not predictable except as the season progresses and the pattern of expression of the controls unfolds during the autumn and/or winter months."

Ground based observations are different from satellite analysis of phenology. The capacity of satellite sensors detecting phenological events (i.e. budding and flowering) is limited due to ground resolutions of the sensors. In addition, the effects of other vegetation and soil background characteristics effect satellite sensors to detect phenology on the ground. Though satellite sensors are limited in capacities, they are still capable of measuring changes in the landscape which may not relate to phenological events of specific plants, nonetheless are descriptive of ecosystem condition (Reed et al., 1994). Annual grasses, such as in California and desert grasslands, have less phenological patterns due to their dependent on less reliable rainfall events. Desert shrublands have photosynthetic activity and phenological events that are moisture related (Reed et al., 1994). Water availability in early spring seems to be reliable in both cold and warm desert in the United Sates because moisture is stored over the winter (Reed et al., 1994). The seasonal behavior of vegetation is an important factor of image interpretation (Reed et al., 1994).

Although drought refers specifically to decreased precipitation, the environmental impacts of drought come from the interaction of multiple ecological processes. In particular, the impacts of drought in Diné Bikéyah are complicated because of the interactions of precipitation, land cover, and indigenous livelihood practices, particularly livestock keeping. Draut, Redsteer, and Amoroso (2012b) shows that the Diné lifestyle and economy have been tied closely to livestock production and husbandry for several centuries. For more than a century it has been recognized that livestock populations can overgraze the lands and reduce native vegetation, especially when livestock impacts are intensified because of drought, which can damage vegetation and increase soil erosion. In Diné Bikéyah, grazing impacts also include the increased abundance of weedy plants, such as the Eurasian annual plant Russian thistle (tumbleweed, plants of the genus *Salsola*) that can spread quickly on sandy soils. Russian thistle can disperse great distances by wind and is one of the most invasive plants on Diné Bikéyah. Thus, the potential impacts of drought are multiple, and might include an increase in vegetation density, but in plants that are not useful to livestock.

More broadly, beyond Diné Bikéyah, (Wilhite, 2000) argues that limited landscape-scale monitoring makes it difficult to pinpoint impacts of livestock on ecosystems. Bradley and O’Sullivan (2011) address the ways that livestock grazing is an important form of land use, affecting ecosystems worldwide. They state that the extent of impact differed depending on elevation. Bradley and O’Sullivan (2011) argue that grazing impacts are heterogeneous spatially on the landscape and depend strongly on stocking rates and elevation (correlated with precipitation). Other scholars argue that intensive grazing may lead to decrease in biomass, soil disturbance and change in species assemblages (Adler, 1976; Belsky, 1987; Belsky, Matzke, & Uselman, 1999; Biondini, Patton, & Nyren, 1998; Bork, West, & Walker, 1998; Harniss & Wright, 1982; Milchunas & Lauenroth, 1993; O’Connor & Pickett, 1992; Schuman et al., 1999; Weber et al., 1998). In the arid western US, Manier and Hobbs (2007) showed that long periods of intensive grazing can change sagebrush steppe by altering plant community composition, biological diversity, and various ecosystem functions such as changes including a reduction in herbaceous primary productivity with increased dominance of shrubs. Studies done by Diouf and Lambin (2001), Vicente-Serrano (2007) and Washington-Allen et al., (2006) show that remote sensing can provide insight on spatial relationships between drought, grazing, and land-cover change.

## 1.4 Research Objectives and Questions

The purpose of this research is to identify land cover changes associated with short-term drought in the Tselani-Cottonwood Chapter (TCC), Arizona (AZ), from 1998 to 2009, during a drought that officially lasted from 1999-2009 (Redsteer et al., 2012). This research seeks to answer the question,

How did land-cover change during this period of drought (1998-2009)?

Given that there are multiply factors that influence long-term land cover change and short-term productivity and success of individual plant species responses during drought. Remote sensing offers the ability to detect changes on the landscape by linking changes to vegetation phenology.

# Chapter 2 Methodology

## 2.0 Overview

## 2.1. Study Area

Diné Bikéyah is located within the four corners region of Arizona, New Mexico, Utah and Colorado. Within Diné Bikéyah lies the Navajo Indian Reservation, designated through treaty with the US in 1868. (None of the reservation lies in Colorado). The reservation is approximately 27,400 square miles (71,000 ha) and is the largest land area assigned to an Indian reservation within the United States, nearly the same size as the state of West Virginia. The Navajo Nation—the tribal government—is divided into five agencies: Northern, Western, Eastern, Central, and Southern. Each agency is sub-divided into chapters, which is the basic unit of local government in the Navajo Nation, similar to municipalities. There are 110 chapters within the five agencies. The Chapter system was created in 1922 as a means of managing agricultural problems at a local level.

The study area is located within Tselani-Cottonwood Chapter, AZ (Figure 1). The study is located at 36° 8' 4.882" N, 109° 47' 9.580" W to 36° 1' 28.666" N, 109° 36' 53.221" W. In the study area, the elevation ranges from 5,840 to 6,000 feet (1870 m to 1829 m). In TCC, total annual precipitation for each year range from 8 to 22.2 mm for the study period based on PRISM climate data, see Table 1 for 1997, 1998, 2000, 2002, 2005, 2009, and 2010.

The main drainage in the TCC is the Cottonwood Wash. This wash runs through the southern part of the study area along with other unnamed intermittent tributary drainages. There are several ephemeral ponds that are filled during the rainy/monsoon seasons. Several windmills and wells are in the TCC area, which serve local water usage. Residents have created earthen dams to collect rainwater for their livestock. Local ponds and watering holes are used for livestock (Weisiger & Cronon, 2009).

The sediments and soil types include alluvial, colluvial, and aeolian sand deposits along with silt and clay (Draut, Redsteer, & Amoroso, 2012a; Draut et al., 2012b; Weisiger & Cronon, 2009). The fine sandy clay loam soil typical of coppice dunes can be found interspersed with sandstone mesas and rocky high plateaus.

Vegetation density is moderate on the higher mesa areas and very sparse along the flood plain areas (Draut et al., 2012b). Figure 2 shows characteristic vegetation on the landscape. Important plant species include shrubs such as: sage brush (*Artemisia tridentate*, *Ts’ah*), rabbit brush (*Chrysothamnus nauseosus*, *K’iiłtsoí nitsaaígíí*), snakeweed (*Gutierrezia sarothrae*, *Ch’il diilyésiitsoh*), russian thistle (*Salsola Kali*, *Ch’il deeníní*), prickly pear cactus (*Opuntia monacantha*), cholla cactus (*Opuntia acanthocarpa*), wolfberry (*Lycium barbarum*, ha*asch’éé’dąą’*), greasewood (*Sarcobatus vermiculatus*, *Díwózhiishzhiin)*, narrow leaf yucca (*Yucca angustissima Engelm*, *Tsá;ászits’óóz*), and tamarisk (*Tamaricaceae*, *Gad ni’eełii bílátah łichí’ígíí*). Grass species include: cheat grass (*Bromus secalinus L.*), grama grass (*Bouteloua gracillis*, *Tl’oh nátasí*), and Indian rice grass (*Oryzopsis hymenoides*, *Nididlídii*) (Mayes et al., 1989). Warming temperatures and recent drought have contributed to vegetation loss in the study area, with additional impacts from grazing and by the spread of invasive plants on sandy soils (Draut et al., 2012b).

Diné occupants in the area occupy small homesteads, which are established near Navajo Bureau of Indian Affairs (BIA) Route 4 and US Highway 191. These homesteads are scattered across the landscape and have been serviced with modern developments including electricity, piped water, and sewer lines (Weisiger and Cronon, 2009). The community of TCC is 5 miles northeast of the study area, 17 miles southwest of Chinle, AZ, and approximately 25 miles east of Pinon, AZ. There has been an increase of homesteads in the past few years with new homes and mobile homes. Locals are expanding their homes has younger generations return to their community (Weisiger & Cronon, 2009).

Diné habitation sites within the area range in dates from the Navajo Long Walk era (1860s) to the present (Weisiger & Cronon, 2009). habitation areas have the traditional styles of the forked stick hogans, cribbed log hogans, and the newer circular hogans built out of milled lumber. The Navajo homesteads have wood frame homes, mobile homes, hogans, sheds, shade houses or ramadas, outhouses, and livestock corrals. Residents still raise sheep, goats, cattle and horses that they tend to everyday and are an important part of their economic livelihood. The livestock graze and forage in the open range (Kuznar, 2001; Weisiger, 2007), leaving trails that transect the landscape.

## 2.2. Materials and Data

### 2.2.1. Precipitation

The study area receives moisture primarily from winter snow melt (during January to March) and summer monsoonal precipitation (July-September). Precipitation varies substantially from year to year, which causes variations in soil moisture and the timing of vegetation phenophases. The average monthly precipitation for each study year in TCC ranges from 8 to 22.2 mm (Table 1). Precipitation occurs bimodally in the southwestern United States, during winter storms (December–March) and the North American monsoon season (July–September). On average, 45% of annual precipitation falls during the summer monsoon (Redsteer et al., 2012). For most of the past century precipitation values have been fluctuating as illustrated by the Palmer Drought Severity Index (PDSI) (Figure 3) and climate has been warming more rapidly in the southwestern United States than in many other regions of North America, resulting in associated ecological changes (Seager, 2007; Weiss et al., 2009; Westerling, 2006). In Figure 4, the precipitation data from the 1950s drought event is compared to the recent precipitation data from 1999 to 2009 drought period. Historical precipitation from 1942 to 1956 and 1997 to 2010 show precipitation over 50 years. A comparison of the recent drought with that of the 1950s, focusing on the four driest consecutive years for each: 2000–2003 and 1942–1952, respectively.

### 2.2.2. Livestock count

The number of livestock grazed (Table 2) in the area was obtained from the Navajo Nation Division of Natural Resources, Department of Water Resources (http://www.dnr.navajo-nsn.gov/). These unpublished data are used with approval from the Department of Water Resources (DWR). The Taylor Grazing Act (43 U.S.C. §315-316) was enacted on June 28, 1934, and was the first federal effort to regulate grazing on federal public lands. This act led to the establishment of grazing districts and to permitting systems, to manage livestock in the districts on the reservation that remain important for Diné livestock production. Each chapter’s grazing committee must work closely with the districts to set the herd size for each range. In 1937, grazing regulations adopted by the Tribe established District boundary lines and carrying capacities. In 1941, the first grazing permit was issued. In 1953, the District Grazing Committee was formed. In 1956, revised grazing regulations were approved, adopted and adjusted to their present boundaries. Navajo Nation DWR recorded livestock counts for 1998 and 2000. Data on livestock numbers for other years, whether before or during the study period, were unavailable.

### 2.2.3. Satellite Imagery

The satellite imagery used in this research is acquired from the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (USGS, 2014) (available online at: http://earthexplorer.usgs.gov/). All Landsat scenes were atmospherically corrected, cloud-free scenes with no scan lines, from path 36, row 35. Landsat 5 TM imagery for 1998, 2002 and 2009 was selected for this research (Table 3). The sequence of dates showed trends with respect to vegetation phenology. In semi-arid environments, the Landsat selection was based on the growing season (late summer monsoon) in late July and August (Reed et al., 1994; Senf et al., 2015; Weiss et al., 2004). Images were selected to fall as closely as possible to the same data for each year to reduce errors caused by the acquired angle, the season, and the differences in reflectance (Vorovencii, 2014). Landsat data were selected because they offer long temporal archive (40+ years), 16-day repeat acquisition time and is affordable (free in many cases), opposed to other satellite systems (i.e. SPOT, MODIS, etc.) (Holden & Woodcock, 2016; Roy et al., 2016).

Landsat has been an important data source in many studies of vegetation classification and change detection (Birtwistle et al., 2016). Since the launch of Landsat

7 in April 15, 1999 the orbital frequency is 16 days (Cohen & Goward, 2004). This allows the user to have access to approximately two images of the same scene each month, given cloud-free images to get a clear view of the Earth's surface. Landsat 7 was selected because of its long temporal archive and because it can be easily acquired at no cost. Landsat 7 mission went perfectly until May 2003 because of a hardware component failure of its Scan Line Corrector (SLC). The impact of the failure where the SLC is stuck in one position is that there are gaps and overlaps between scans, therefore selecting imagery for the study area is limited. Landsat 8, launched in 2013 continues the legacy of the Landsat program by providing no cost (freely available since 2008), much higher quality and quantity Earth observations vital to time series investigations (Holden & Woodcock, 2016).

In this study, the available images for the study area of each year are sufficient for the comparison and determination of the effects of drought and identify land cover types.

### 2.2.4. Calibration and Validation Data

To analyze the spectral characteristics of typical five land cover types in the study area and assess the accuracy for five classification (Table 4), calibration (or training) and validation (or reference) pixels for all land cover categories were collected from the Landsat 5 TM images by selecting visual interpretation of Google Earth (WorldView-1 imagery with 0.5 m nadir resolution, acquired between August 1998 and August 2009) images. Calibration and Validation pixels were selected using visual interpretation based on prior knowledge of the study area. Calibration and validation data were selected in ERDAS IMAGINE processing software. The validation data were classified as dense shrub, dense grassland, sparse shrub, sparse grassland and barren land classes (Figure 6) with 20, 20, 20, 20 and 20 pixels, respectively. In total, 600 pixels were selected from Landsat 5 TM images. Furthermore, a decision mapping classifier rule of 60% cover of a 5x5 dot grid matrix of these pixels were randomly selected and assigned to the calibration and validation dataset (Figure 7). For the calibration dataset, the numbers of dense shrub, dense grassland, sparse shrub, sparse grassland and barren land were 20, 20, 20, 20 and 20 pixels, respectively.

### 2.3. Decision mapping classifier for land cover classification

Within the study area, the most common land cover classes identified by United States Geological Survey (USGS) are Forest and Woodland, Shrubland and Grassland, Semi-Desert, Non-vascular and Sparse Vascular Rock Vegetation, Agricultural Vegetation, Developed and Other Human Use, Introduced and Semi Natural Vegetation and Open Water (Figure 8). This mapping classifier is single stage, where only one decision is made about a pixel, which is labeled as belonging to a class or is left unclassified. The classification rule is in the form of ‘‘IF condition, THEN action’’ statements. The condition portion of a classification rule is a 60% cover within a pixel, and the action portion is a decision (e.g., next class). A dot-grid matrix was generated and overlaid on the reference imagery. Twenty-five sample points were laid out per pixel. Five land cover types were discernable in the reference imagery and recorded: dense shrub, dense grassland, sparse shrub, sparse grassland and barren land. Land cover types directly coincident to each point were visually determined.

### 2.3.1. Image Pre-processing

All Landsat 5 TM and Landsat 7 ETM+ scenes were georeferenced prior to downloading, to comply with the L1T Level 1 Product Generation System (LGPS) standard using 222 Ground Control Points with 3.872 root-mean-square-error (RMSE). Landsat bands consisted of six bands (blue, green, red, NIR, SWIR1, and SWIR2) and each image was stacked using ERDAS IMAGINE 2013. The stacked layers were subseted to the study area (540 km$^2$). Two roads were masked out of the 1998 image and three roads were masked out of 2002 and 2009 images.

### 2.3.2. NDVI Analysis

In ERDAS IMAGINE, NDVI was applied to all Landsat images. All NDVI Landsat images were opened in ArcGIS 10.2.2. to be reclassified using the spatial analysis tool (reclassified). The reclassify tool was used to set a threshold at 0 and 1.5 to reclassify (or change) the values in a raster.

*Equation 1 NDVI*

$$NDVI = \frac{\mathrm{NIR-RED}}{\mathrm{NIR+RED}} \qquad \text{where } (-1<\mathrm{NDVI}<1)$$

NDVI values range from [+1, -1]. Low values of NDVI (0.1 and below) correspond to barren areas of rock, sand, or snow. Bare soil has an NDVI close to 0, and water bodies are represented with negative NDVI values. Moderate values correspond to shrub and grassland (0.2 to 0.3). High values represent temperate and tropical rainforests

(0.6 to 0.8) (Gandhi et al., 2015). Threshold values for no vegetation were set to 0 – 1.5, while values higher than 1.5 were considered shrubland and grassland (Weiss et al., 2004). The reclassified NDVI images used Equation 2 to quantify area of vegetation within each image.

*Equation 2 Area of pixel*

$$\frac{N * 30\ m^2 * 30\ m^2}{1{,}000{,}000} = area\ of\ pixel\ in\ km^2$$

In Equation 2, N is the total number of pixels calculated with one NDVI value for each year (Table 5).

### 2.3.3. Supervised Classification

Landsat images for 1998, 2002 and 2009 were used to conduct supervised classification. Supervised classification was carried out using Landsat TM images in order to classify the image into five (5) classes and to identify potential change classes. Supervised classification was done using image references points from Google Earth. The area was classified into five classes. Land cover classes considered were dense shrub, sparse shrub, dense grassland, sparse grassland and barren land. Description of these land cover classes are presented in Table 4. It can be noticed that some spectral classes corresponded to various covers with spectral similarities.

### 2.3.4. Accuracy Assessment

Accuracy assessment was carried out using 300 points (20 points per class for each year) from Google Earth as a reference image. The location of the 300 points were chosen using simple random method to represent different land cover classes of the area. Based on the validation sample (300 points), calculation was done for confusion matrices for each classification and estimated overall, producer's and user's accuracies. The accuracy of the supervised (maximum likelihood) classified images was compared to the image reference data for 1998, 2002, and 2009. Accuracy assessment calculation is shown in Table 7.

### 2.3.5. Spectral analysis of land cover

Based on calibration data, the spectral reflectance and spectral indices of all land-cover types were analyzed. The spectral analysis of land cover is helpful for understanding spectral similarities (and differences) among these land-cover types (e.g. dense shrub, dense grassland, sparse shrub, sparse grassland and barren land). Visual inspection of spectral shape and overlap between land cover classes across the electromagnetic spectrum allowed for the assessment of land cover class separability for each year (Figure 10).

## 2.4. Change Detection

In this study, post-classification change detection technique was applied. Post-classification required the comparison of independently produced classified images. Cross-tabulation analysis was carried out to analyze the spatial distribution of different land cover classes and land cover changes. The tabulation of one image compared to the second image (e.g. 1998 to 2002 and 2002 to 2009) is kept of the number of cells in each combination. The result of this operation is a table listing the tabulation totals. Two change-detection analyses were performed: One based on NDVI values, which allowed for the identification of vegetation and no vegetation classes, and another based on the supervised classification land cover classes (e.g. dense shrub, dense grassland, sparse shrub, sparse grassland and barren land).

# Chapter 3 Results

## 3.1. Evaluation of NDVI

NDVI values were generated for 1998, 2002 and 2009 using Red and NIR bands of the Landsat images (Table 5). The NDVI images occupied by vegetation cover have NDVI values between 0 and 1.5, where higher values are associated with greater density and greenness of plant canopy (Chen et al., 2004). The amount of vegetation fluctuated during the study period. In 1998, the amount of vegetation was greatest, with 398.7 km$^2$ vegetated within the 540 km$^2$ study area. In 2002, the amount of vegetation was the lowest of the three dates (180.6 km$^2$), and in 2009 vegetation increased (367.7 km$^2$).

## 3.2. Evaluation of supervised classification

Five classes (dense shrub, dense grassland, sparse shrub, sparse grassland and barren land) were analyzed in the maximum likelihood procedure for 1998, 2002, and 2009. The quantities of the five land cover classes slightly fluctuated during the study period (Table 6).

Overall, the classification results (Figure 9) showed the sparse grassland and barren classes had the highest proportion of land cover throughout all years while dense shrub had the lowest proportion throughout all years. Sparse shrub slightly decreased from 1998 to 2002 (3 km$^2$). Sparse grassland decreasing substantially during this period (140 km$^2$). The amount and timing of high summer seasonal variation of grassland is dependent on large rainfall amounts and is a function of water availability (Weiss et al., 2004). Dense shrub, dense grassland, and barren land increased from 1998 to 2002 (3 $km^2$, 62 $km^2$, and 79 $km^2$, respectively). Regarding the Colorado Plateau grassland and shrub-steppe, higher amounts of summer precipitation allow increased growth (Weiss et al., 2004). Dense grassland decreased from 20.5 $km^2$ in 2002 to 14.2 $km^2$ in 2009 while barren land decreased from 63.1 $km^2$ 2002 to 38.9 $km^2$ 2009. Dense shrub, sparse shrub and sparse grassland increased from 2002 to 2009 (102 $km^2$, 37 $km^2$, and 26 $km^2$, respectively).

### 3.3. Accuracy Assessment

The error matrix is shown in Table 7. According to Lang et al., (2008) an accuracy lower than 85% seems unacceptable. Overall accuracy was 91% for 1998, 90% for 2002 and 93% in 2009. Overall, the determined land-cover mapping accuracy of approximately 90% to 93% indicates that the integration of visual interpretation with the supervised classification of remote sensing imagery is an effective method for the identification of changes in landcover.

The overall accuracy only incorporates the major diagonal and excludes the omission and commission errors. Depending on the amount of error included in the matrix, these measures may not agree. It is not possible to give precise rules as to when each measure should be used. Each accuracy measure incorporates different information about the error matrix and therefore must be examined as different computations attempting to explain the error shown in Table 7.

### 3.4. Spectral separability

Spectral curves of all spectra collected for each class (dense shrub, dense grassland, sparse shrub, sparse grassland and barren land) were plotted for each collection date (Figure 10). Separability was visually determined between bands and vegetation index values for all classes. The spectral analysis of land cover showed spectral similarities among these land-cover types (e.g. dense shrub, dense grassland, sparse shrub, sparse grassland and barren land). Therefore, further recommendation to combine similar classes and generate new land cover classes based on spectral analysis.

### 3.5. Change Detection

Multi-date post-classification change detection results shown in Table 5 and Table 6. Table 5 shows the total areas of vegetation for each year. From 1998 to 2002, vegetation decreased by 218.08 km$^2$, while from 2002 to 2009 vegetation increased to 187.17 km$^2$.

Table 6 represents the total areas of each land cover class for each year. In 1998, barren land and sparse grassland were the largest class, representing 49% (263 km$^2$) and 32% (174 km$^2$) of the total land cover classes assigned. In 2002, barren represented 63% (341 km$^2$) while sparse grassland represented 6% (34 km$^2$). In 2009, barren land decreased to 39% (211 km$^2$), although sparse grassland increased to 11.2% (61 km$^2$).

Table 2 characterizes the total livestock tally counts for the entire chapter of Tselani-Cottonwood for 1998, 2000, and 2003. Although there are no data for 2002 and 2009, the count from 1998, 2000, and 2003 shows a decrease in livestock. The limited available data from the Division of Water Resources shows no major change in the number of livestock in the chapter during this period. Based on the NDVI threshold method, from 1998 to 2002 vegetation decreased by 1.2 $km^2$ however, livestock data (Table 2) show a decrease from 5,182 to 4,537 tally counts. Even though numbers are for the entire TCC and there are no data for most years, and while the whole reservation experienced drought, the numbers did not significantly change over each year. In addition, the landscape was used for grazing consistently throughout each year during the ten-year drought period. Based on their limited data, there is no reason to believe that significantly fewer or more animals were grazed in the study area from 1998 to 2009.

# Chapter 4 Discussion and Conclusions

## 4.0 Discussion and Conclusions

The primary objective of this research was to identify and quantify land-cover changes during a ten-year drought period. Historical and paleoclimatic observations indicate recurring periods of drought in the southwest (Weiss et al., 2009), which means that understanding land-cover changes associated with drought is important for understanding potential impacts of drought on Diné livelihoods.

Weisiger (2007) reported evidence of significant droughts in the 1100s, 1250s, and the late nineteenth century. The 1870s and 1880s were extremely dry according to tree-ring data, and in 1899 to 1904, Diné Bikéyah received little snow and rainfall for some years. Weiss et al., (2009) stated that the most notable southwest droughts are those that occurred in the late 1890s to early 1900s, the 1950s, and most recently the early 2000s. Weiss et al., (2009) concluded that the southwest is particularly susceptible to drought due to its variable, semi-arid climate.

Due to the arid climate, drought has always been a major concern to Diné. Currently, Diné Bikéyah is still recovering from the drought that lasted from 1999-2009 (Redsteer et al. 2012). This may be the longest drought in recent history in Diné Bikéyah, lasting longer than other droughts of the 20th century. As climate change is predicted to increase (Pachauri et al., 2014) in the Southwest, identifying potential land cover changes in Diné Bikéyah is important. Drought response on Diné Bikéyah is not a luxury, but drought instead costs local Diné residents heavily because the livelihoods of many people depend upon having adequate vegetation to pasture livestock. Although the data on livestock numbers in this study do not cover the whole study period, there is no evidence that people in the TCC reduced the number of animals they kept despite the drought. Table 3 shows the number of livestock for the entire TCC, all of which experienced drought during 1999-2009.

Livestock reduction is an approach to herd management that carries great meaning in current Diné society. The treaty of 1868 with the US created the Navajo Indian Reservation within Diné Bikéyah. Bailey and Bailey (1986) explains that Diné and the US have frequently disagreed over practices of livestock management. Only a small portion of rangeland was designated within the original boundaries of the reservation. Then, between 1868 and the mid-1930s the number of livestock on the reservation tripled. As population grew and livestock increased, livestock numbers fluctuated year by year due to drought, other ecological factors, and social-economic factors. During the 1920s, the federal government decided that the land could not support the number of animals, because of concerns about erosion due to overgrazing. Thus, Bailey and Bailey (1986) and Weisiger (2007) explain that federal officials decided the best approach to managing pasture conditions was to drastically reduce the number of livestock being pastured.

Federal officials appointed John Collier, the commissioner of Indian Affairs, to pursue livestock reduction as part of President Franklin D. Roosevelt's New Deal. The federal government enforced livestock reduction in various parts of the reservation, although it did not appear everywhere and did not arise immediately. In those areas in which livestock reduction was enforced, many families were devastated because they lost their source of income (Parman, 1976). For more than a century Diné people have recognized that livestock populations can overgraze the lands and reduce native vegetation (Draut et al., 2012b). However, the Diné people opposed stock reduction in the 1930s (Bailey & Bailey, 1986; Weisiger, 2007).

Historically, the Diné lifestyle and economy have been tied closely to livestock production and husbandry. Many Diné families cherish livestock as a source of food, clothing, rugs, prestige, and wealth. Livestock have been culturally significant for centuries. Diné women learned the art of weaving, and by the mid-1800s they were producing rugs for wholesale. In the 1890s, an increasing number of tourists demanded Diné blankets and rugs. Weisiger and Cronon (2009) describe Diné woman as expert weavers, and explain that weaving was a very valuable trade.

Diné women were particularly affected by livestock reduction. As Weisiger (2007) and White (1988) both argued, when the United States enforced stock reduction they ignored the importance of Diné women. Diné people live in a matricentered society, in which women stood at the center of Diné life and thought (Weisiger & Cronon, 2009). Diné people evolved from an important deity known as Changing Woman who created the Diné and their livestock and gave them different ceremonies. Diné traced lineage thought their mothers. Diné women did not base their power on solidarity but were important in economic production and controlled their own production, by controlling livestock and land. Further, Diné woman were the ones responsible for slaughtering, skinning, and butchering livestock (Weisiger & Cronon, 2009).

In 1934, the government issued a mandate to eliminate goats on Diné Bikéyah. Diné women valued goats in particular because they depended on their milk, cheese, meat, breeding or bartering, and they were hardier and survived winters better than sheep.

Weisiger and Cronon (2009) state that Diné women worked closer to the hogan, raising children, weaving, grinding corn, milking goats, preparing meals, gathering plants and seeds, as well as managing their flocks. Thus, the greater independence of goats compared to sheep was particularly beneficial to women, who could not range widely to watch animals. Thus, Diné women particularly rejected Collier's program, and opposed to stock reduction. However, the government continued to eliminate goats (Weisiger & Cronon, 2009). These animals targeted because they had little market value at the time and considered particularly damaging to land-cover. An example shows how stock reduction happened. A BIA stockman, Carl Beck, purchased 3,500 goats and sheep. Not long after his purchase, Carl Beck realized the animals would not survive the long journey to the nearest road. Therefore, Carl herded them into a canyon to be shot and left for coyotes, buzzards and crows. Other stories such as Weisiger (2007) states that government agencies burned goats alive across Diné Bikéyah. Diné women owned majority of livestock and they particularly experienced anguish, as their goats were slaughter. These Diné women did not forget the powerlessness they felt by the government (Weisiger, 2007). Almost ten years later, in the summer of 1943 the Tribal Council passed a series of resolutions to stop the stock reduction and the conservation program (Weisiger, 2007). Roessel and Johnson (1974) argued the Diné experienced stock reduction in various ways. This depended on where they lived, geographical isolation, social position, wealth, gender, education, and so forth.

Collier had good intentions when he tried to enforce the New Deal program on the Navajo Reservation. Collier's intention was to prevent another Dust Bowl situation by addressing livestock, drought, and arroyo-cutting rains had aggravated the land.

However, John Collier did not understand the meanings livestock held for Diné people. Additionally, livestock reduction was biased against Native Americans, particularly the Diné. Most of the American West is grazed: approximately 70% supports livestock (Floyd, et al., 2003). Nonetheless, Weisiger and Cronon (2009) state that US conservationists focused on overgrazing in native lands, even though, in the case of the desert Southwest, there was a theory that arroyos had been caused primarily by climate changes. The policy of livestock reduction assumed that environmental changes were the consequence of human activities, and did not consider how ecosystems change independently of people.

The physical geographic processes contributing to land-cover changes in Diné Bikéyah are poorly known, and the relative importance of livestock and climate in land-cover changes is particularly poorly known. A study by Gregory (1917), a geologist, studied Diné Bikéyah in the early twentieth century. Gregory (1917) noted that arroyos appeared to be universal across the Colorado Plateau, including in areas left ungrazed, because highly seasonal precipitation could cause erosion despite the limited overall amount of precipitation. Another study by Kirk Bryan (cited in Weisiger & Cronon, 2009) agreed with Gregory's findings, that climate was the cause of arroyo formation, based on previous downcutting in the 1100s near Chaco Canyon. Significantly, this erosion occurred hundreds of years before the arrival of sheep in the sixteenth century by the Spaniards.

Since the 1100s, Diné people knew nature not only by connecting with the physical environment but through the metaphysical world, experienced through the Blessingway ceremony (Weisiger & Cronon, 2009). This ceremony was amongst one of the most important to the Diné people. The ceremony framed to understand the relationship between animals (livestock) and land. Changing woman first gave life to sheep and goats, and in the process created plants that cover the ground. The story of creation by Changing woman, was passed down from generation to generation, pointing out that the Diné people had the most respect for Diyin Dine'é (holy spirits). Kuznar (2001) states that Diyin Dine'é gave the Diné people livestock, and as the sheep and goats were born, their amniotic fluid soaked into the earth, and vegetation grew (Weisiger & Cronon, 2009). Kuznar (2001) strongly states that not only are human and livestock relations important to Diné ideology, but plant ecology is connected as well.

Weisiger and Cronon (2009) describes that Diné people developed detailed knowledge of the plants on which they depended, and encoded some of this knowledge in their names for plants. These names told stories of plants, describing their physical characteristics as well as their value for healing and feeding livestock. Plants are useful to Diné people as food, as livestock forage, and for many other uses. For example, since the mid-1800s, Diné women valued particular plants to dye wool, which came from their sheep and goats. Also, many plants, trees, and shrubs are sacred to Diné people for ceremonial and medicinal information (Kuznar, 2001). Plant use is an important part of life of the Diné people. Kuznar (2001) argues that plants were particularly useful to Diné as sources of food and for medicine, especially in time of hardship. In addition, vegetation helped stabilize erosion and sand mobility. For example, studies by Draut et al., (2012b) and Thomas and Redsteer (2016) in Diné Bikéyah and found that certain species help reduce sand mobility.

Given the importance of vegetation in Diné livelihoods, and the limited knowledge of land-cover changes associated with drought and other climate events, analysis of land cover changes using remote sensing offers the ability to understand how people and livestock might contribute to land-cover change, and to develop sustainable livestock management strategies.

The present study found that land cover changed only slightly in the TCC during a ten-year drought event from 1998 to 2002. Importantly, during this period, vegetation also experienced disturbance caused by livestock grazing (Table 2). The land management that took place during the ten-year drought period certainly affected land-cover throughout the study area. However, observed changes do not correspond to some concerns that have been raised about presumed environmental changes in the desert Southwest. For instance, in the study area, sparse shrub land cover decreased from 6.30% to 5.8%. Yet as Floyd et al., (2003) describe, shrub "invasion" of grassland has been known in the Southwest for decades and is the focus of a great deal of management controversy. There is no evidence that this happened in the TCC during the study period. In fact, Brown (1950) (cited in Floyd et al., 2003) found that shrubs increase more on protected areas than on current grazing areas.

Further, in the study area sparse grassland decreased from 32% to 6.4% based on maximum likelihood analysis. Based on the NDVI analysis, green vegetation decreased slightly from 135.7% to 299.5% of the landscape. Decrease in sparse grassland and NDVI changes suggest a decrease in precipitation (Table 1) from 20.3 mm to 10.5 mm. However, after 2002, land-cover reveals limited change, potentially indicating that the vegetation is resilient to ten-year drought events, even when used as livestock pasture.

This is important to recognize because many Diné people rely on vegetation for their livelihood, and have limited options during droughts. Despite awareness of possible negative impacts on vegetation and ecosystems due to livestock, especially during a drought period, Diné people remain attached to livestock keeping as both an economic need and as a way of life. For instance, in the *Navajo Times* newspaper, Yurth (2008) reported one Diné person as saying, “People say, ‘Why don’t you reduce your herd? You can’t feed your way out of a drought.’ Well, doggone it, this is my life. To me, there’s nothing more satisfying than being out here with my animals. It’s not totally idyllic, but at the end of the day you can say, ‘I did something.”

Historical records indicate that livestock reduction is economically and socially damaging, however, in Diné Bikéyah there is no published evidence that historic stock reduction led to the vegetation changes that US authorities hoped for. The present study has shown that observed variation in vegetation cover was low, even though the area was grazed during a drought period. Because the landscape is mostly barren to begin with, the observed change represents a relatively small overall change in landscape conditions. Even before the drought, in 1998, the landscape was mostly barren. Similarly, supervised classification showed that the area covered by the five land cover classes changed from 1998 to 2002, but the amount of change year-to-year was not large during the ten-year drought period.

Monitoring land cover during droughts is necessary to help Diné people to respond to or recover from the effects of drought. The Navajo Nation government should increase efforts to study land-cover changes associated with climate change as well as livestock management practices. Bitsoi (2013) states in the Navajo Times, a response from Leo Watchman, manager for the Department of Agriculture in 2013, cited poor land management as a contributing factor. He states, “It goes back to management,” in which the tribe currently has no funding to address drought conditions. In addition, Leo Watchman states, “with over 10,000 grazing permittees, its necessary, adding that Navajos have recently become aware of the drought’s impact on rangelands from awareness workshops” (Bitsoi, 2013).

The connections between livelihoods, vegetation, livestock, and climate are complicated. For example, drought affects vegetation, and overgrazing also makes livestock more susceptible to drought. Additionally, grazing often leads to soil compaction (Floyd et al., 2003), increases erosion, and thus damage water quality and supply. Both livestock and vegetation is crucial to traditional Diné livelihoods. If no efforts are being made to balance the livestock numbers on Diné Bikéyah, then it may be counterproductive to provide drought relief to livestock in areas that are over grazed. Yet if there is no knowledge of land-cover changes associated with drought conditions, management decisions are difficult to make. Observing, analyzing, and monitoring land-cover changes in Diné Bikéyah will allow Diné people to create effective adaptation and mitigation strategies to address impacts of drought and climate change more broadly.

## 4.1. Limitations of Research

There are several limitations to this research.  Field derived calibration and validation points (rather than image-reference points) would likely improve classification results. A longer study period, finer spatial resolution imagery and a larger study area, with more precise meteorological, and physical geographic data specifically for the study area, would increase understanding of the relevant physical geographic processes. To improve understanding of cultural ecology of the specific study area, particularly landscape and livestock management, interviews of residents would be valuable. Similarly, more extensive data on the number of livestock in the study area would improve knowledge of their impacts on vegetation. Despite these limitations, this study provides baseline data on land-cover changes associated with drought in Diné Bikéyah.

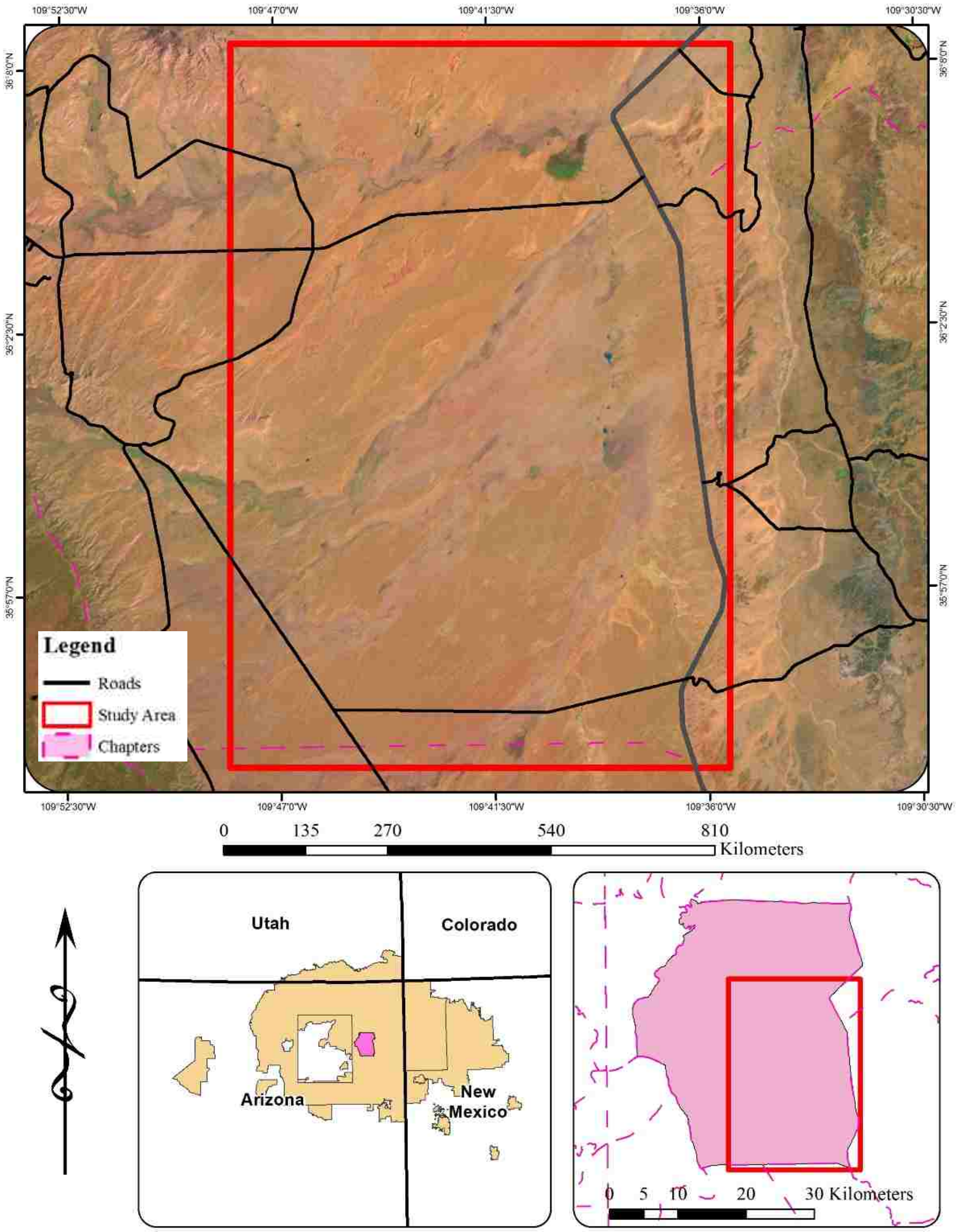
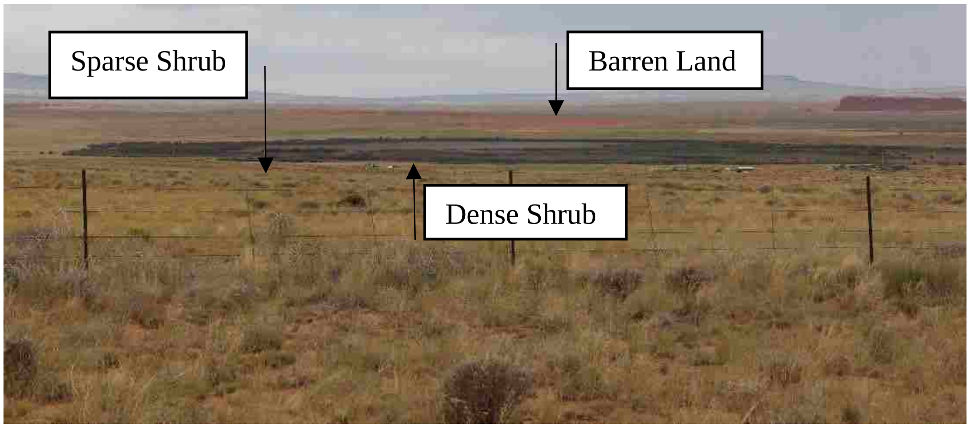
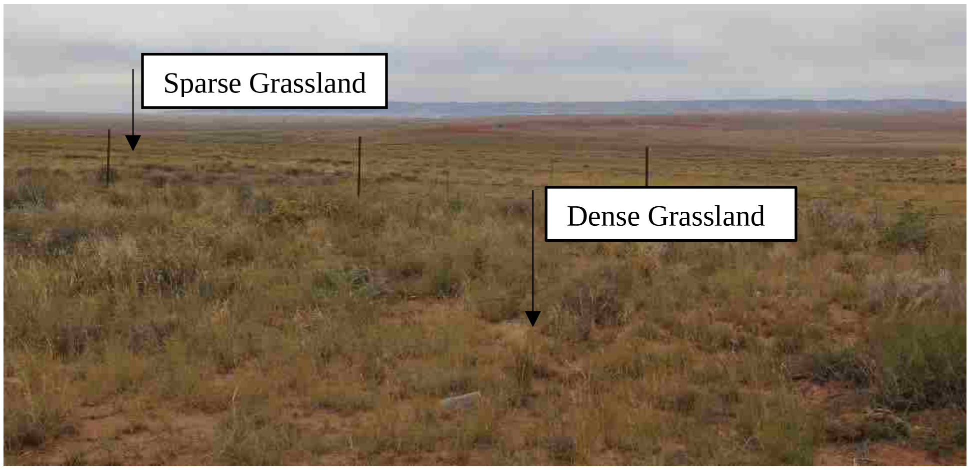


*Figure 1. Study Area of TCC, outlined in pink dash marks/solid pink and Study area outlined in bold red.*



a. Facing west on US 191



b. Facing Southwest on US 191

*Figure 2. Photos of TCC. (a) Photo of Study area facing west on US highway 191 in TCC. (b) Photo of Study area facing southwest on US 191 in TCC. Photo by Anjanette hawk*

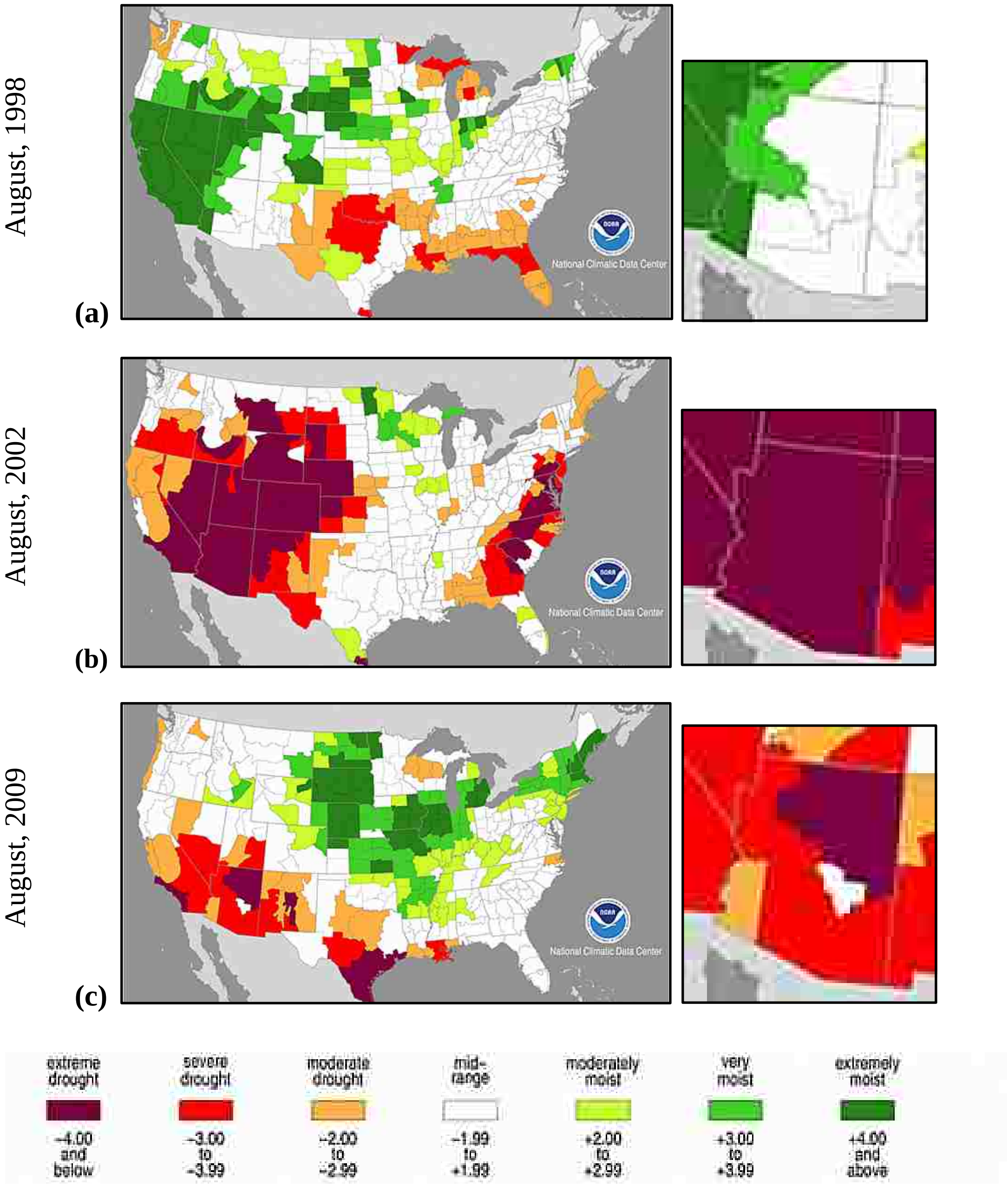
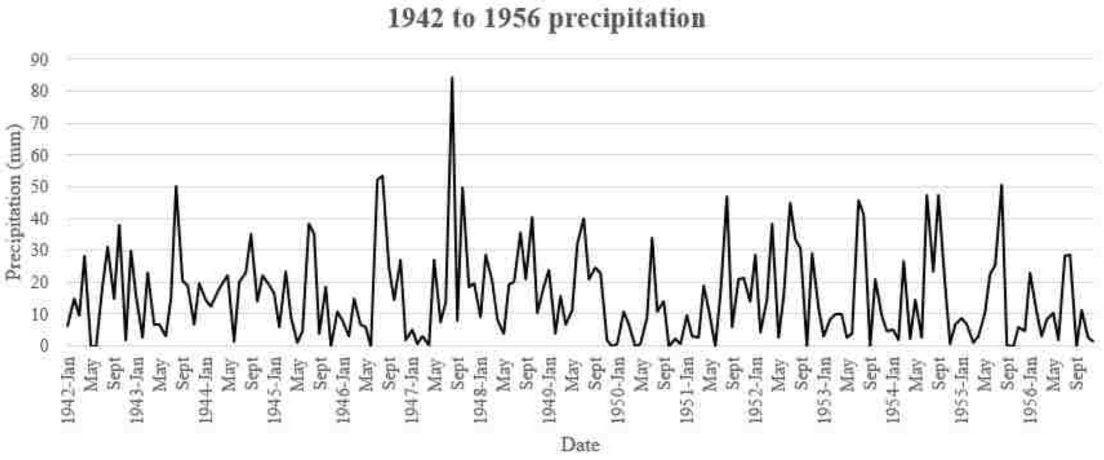


*Figure 3. Palmer Drought Severity Index (PDSI) by NOAA in Arizona: a) Aug. 1998, b) Aug. 2002, and c) Aug. 2009. Color scheme: maroon (-4.0 or below) extreme drought, orange (-2 to -2.9) moderate drought, white (-1.9 to +1.9) near normal, light green (+3.0 to +3.9) very moist, and dark green (+4.0 and above) extremely moist.*



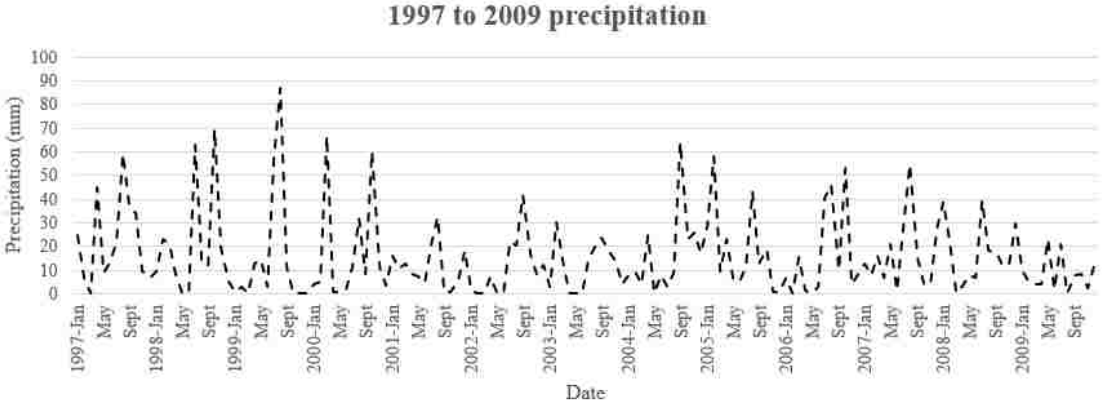
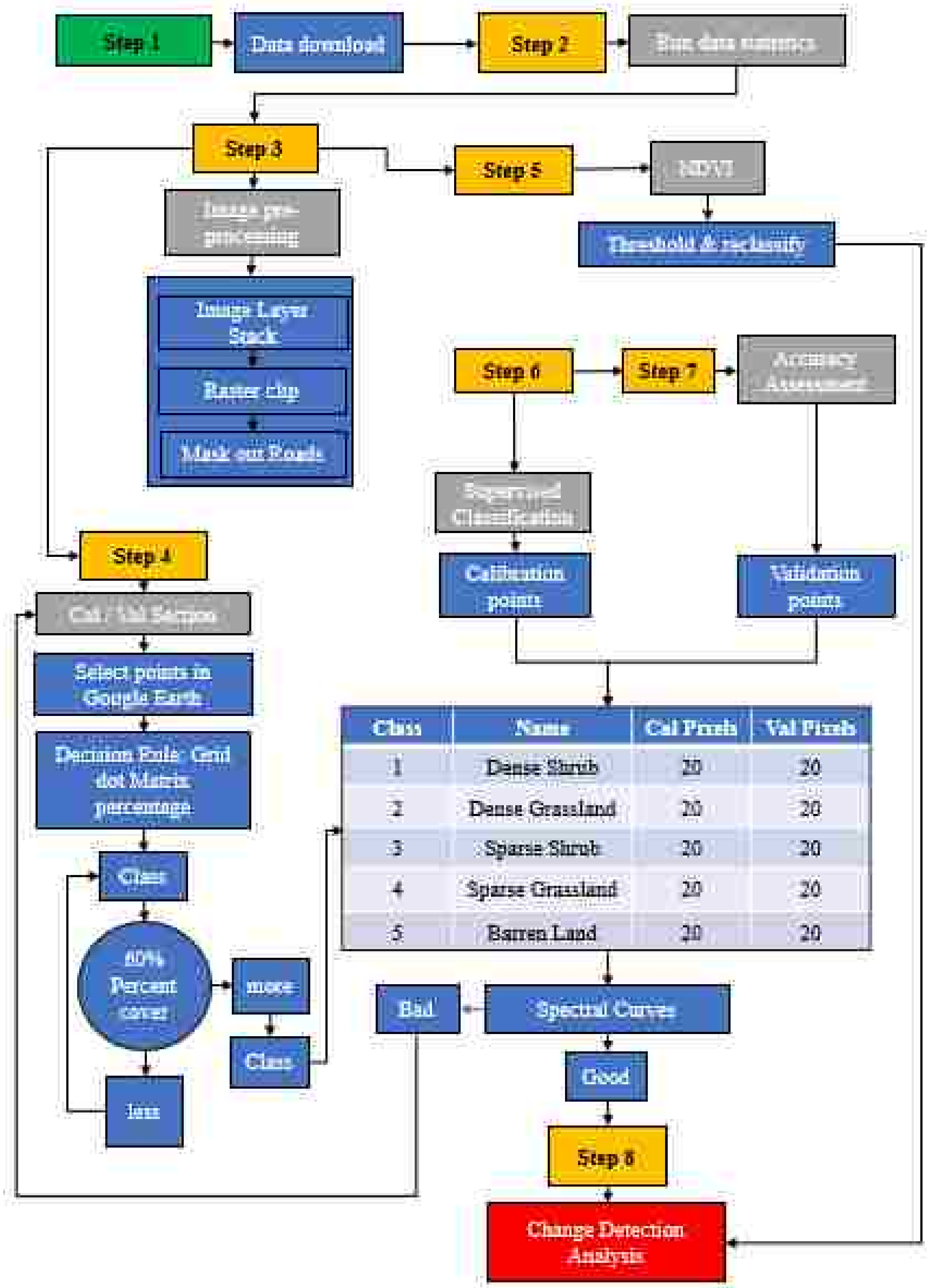
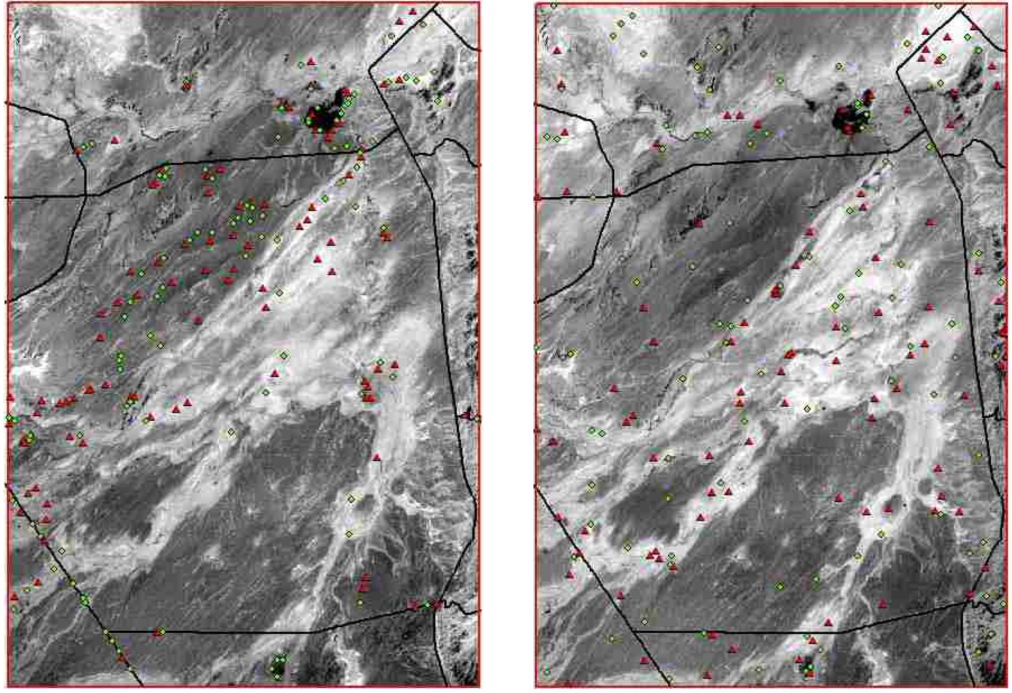


*Figure 4. PRISM precipitation data from 1942 to 1956 and from 1997 to 2009. (http://prism.oregonstate.edu/explorer/)*



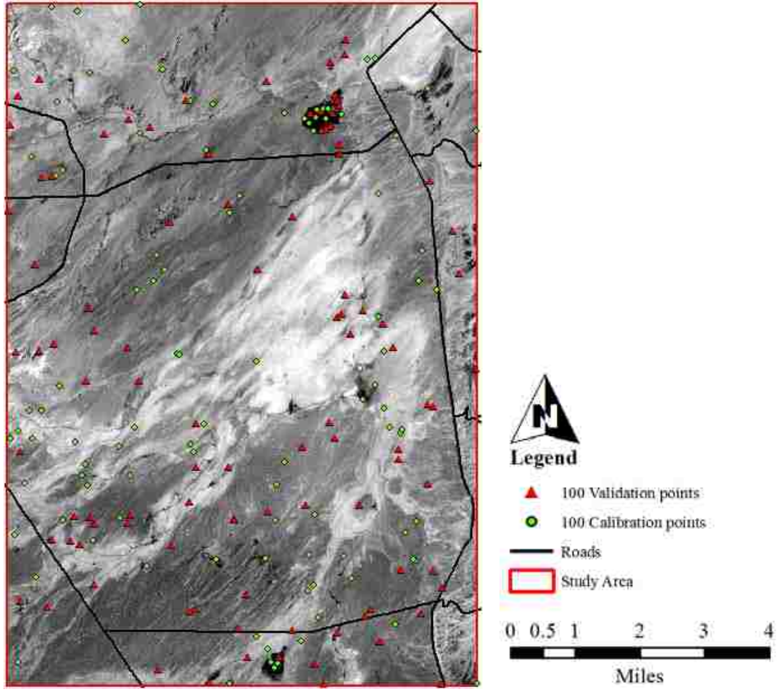
| Class | Name | Cal Pixels | Val Pixels |
|---|---|---|---|
| 1 | Dense Shrub | 20 | 20 |
| 2 | Dense Grassland | 20 | 20 |
| 3 | Sparse Shrub | 20 | 20 |
| 4 | Sparse Grassland | 20 | 20 |
| 5 | Barren Land | 20 | 20 |

*Figure 5. Steps for Method in developing land cover change analysis, from download to results with NDVI, Supervised classification, change detection and accuracy assessment.*



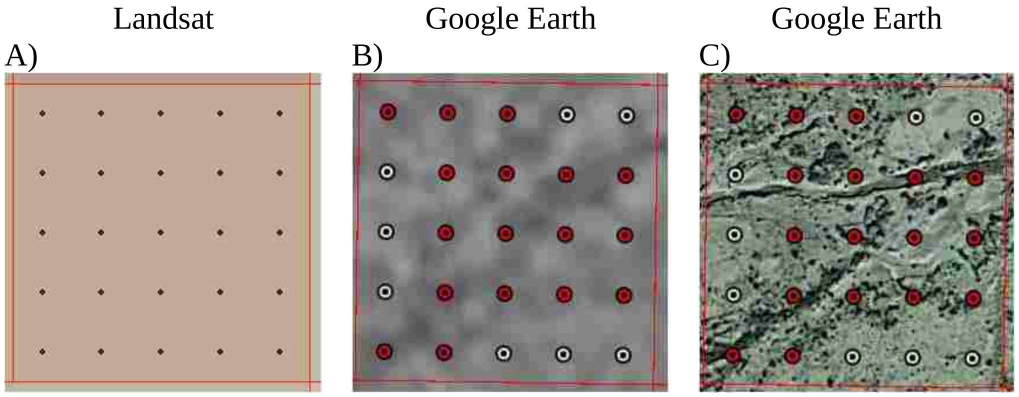
(a) 1998 Landsat imagery

(b) 2002 Landsat imagery



(c) 2009 Landsat imagery

Figure 6. Calibration and Validation data points selected for land cover classes: BL – barren land, DG – dense grassland, DS – dense shrub, SG – sparse grassland, and SS – sparse shrub.



Landsat A) Google Earth B) Google Earth C)

1 pixel (30m x 30m) 5 x 5 dot grid matrix Land cover reference

Figure 7. Example calibration and validation grid dot matrix where A) is a 30 x 30 m plot (1 Landsat pixel) overlay by 25 sampling points. B) and C) contains reference imagery.

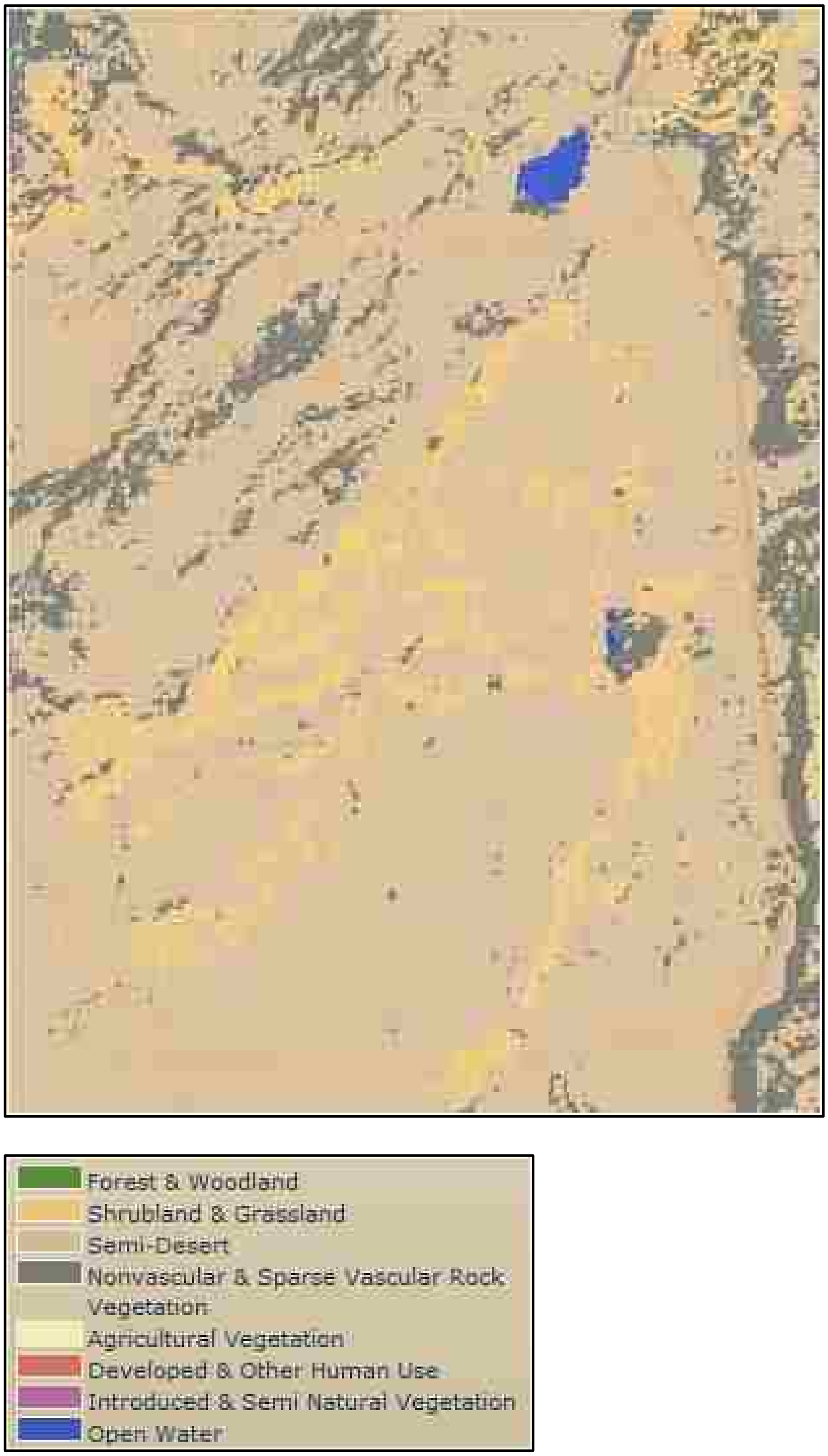
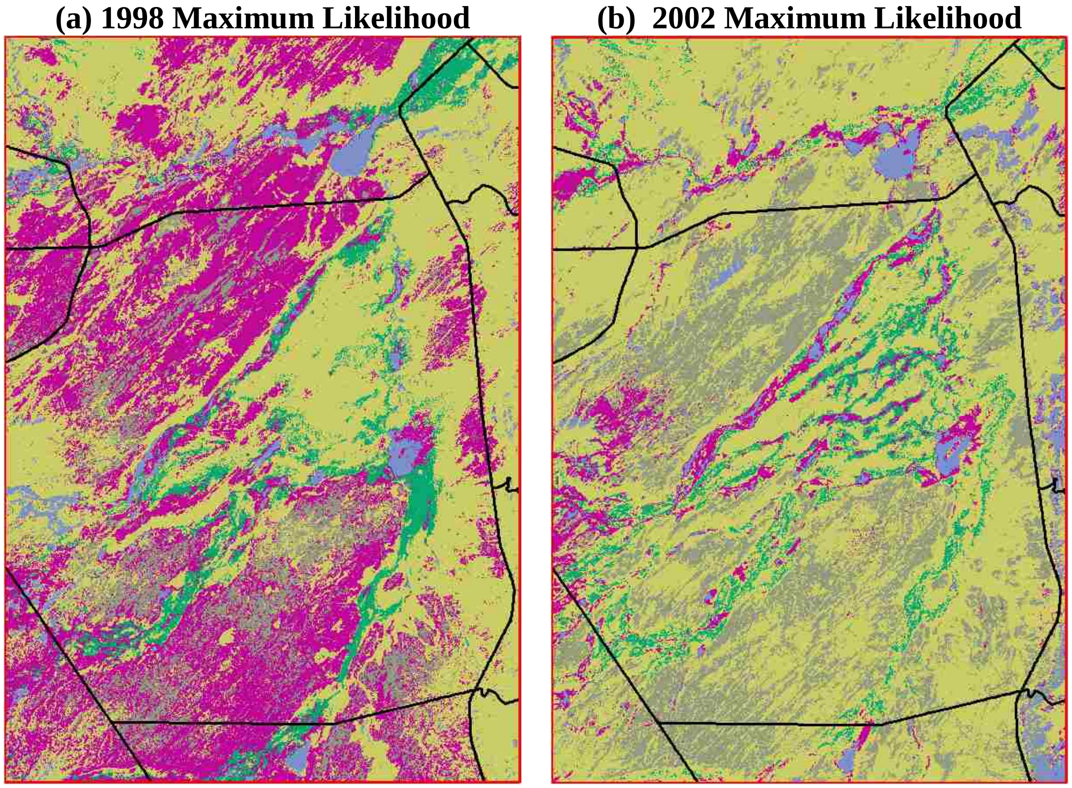


*Figure 8. Land cover across the Study Area, courtesy of USGS National Gap Analysis Program (GAP), http://gapanalysis.usgs.gov/.*



**(a) 1998 Maximum Likelihood**

**(b) 2002 Maximum Likelihood**

**(c) 2009 Maximum Likelihood**

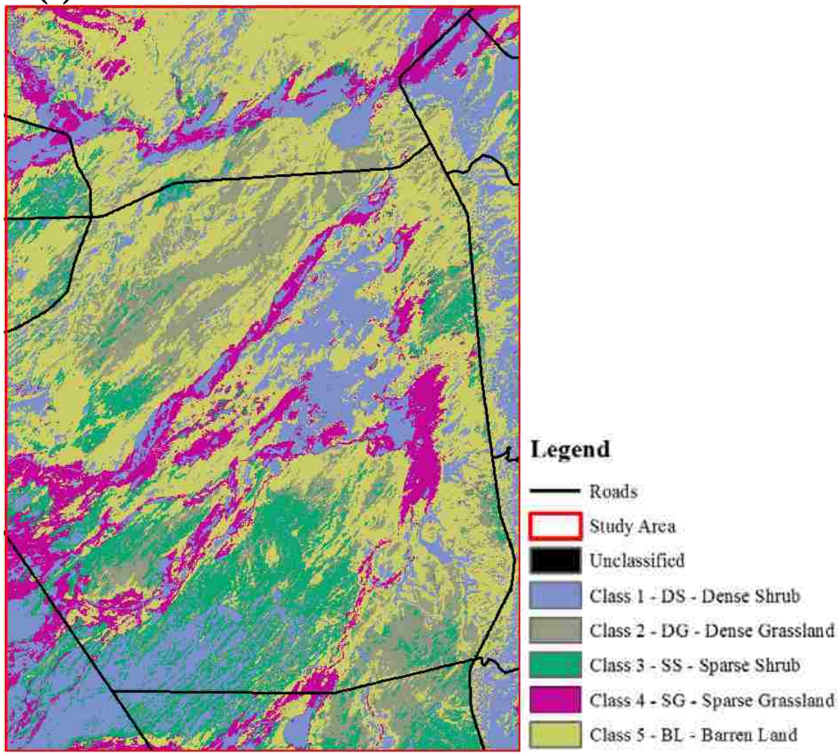


Figure 9. Supervised Classification with 5 classes using Supervised Classification Maximum Likelihood to identify the locations of land-cover classes within the study area.

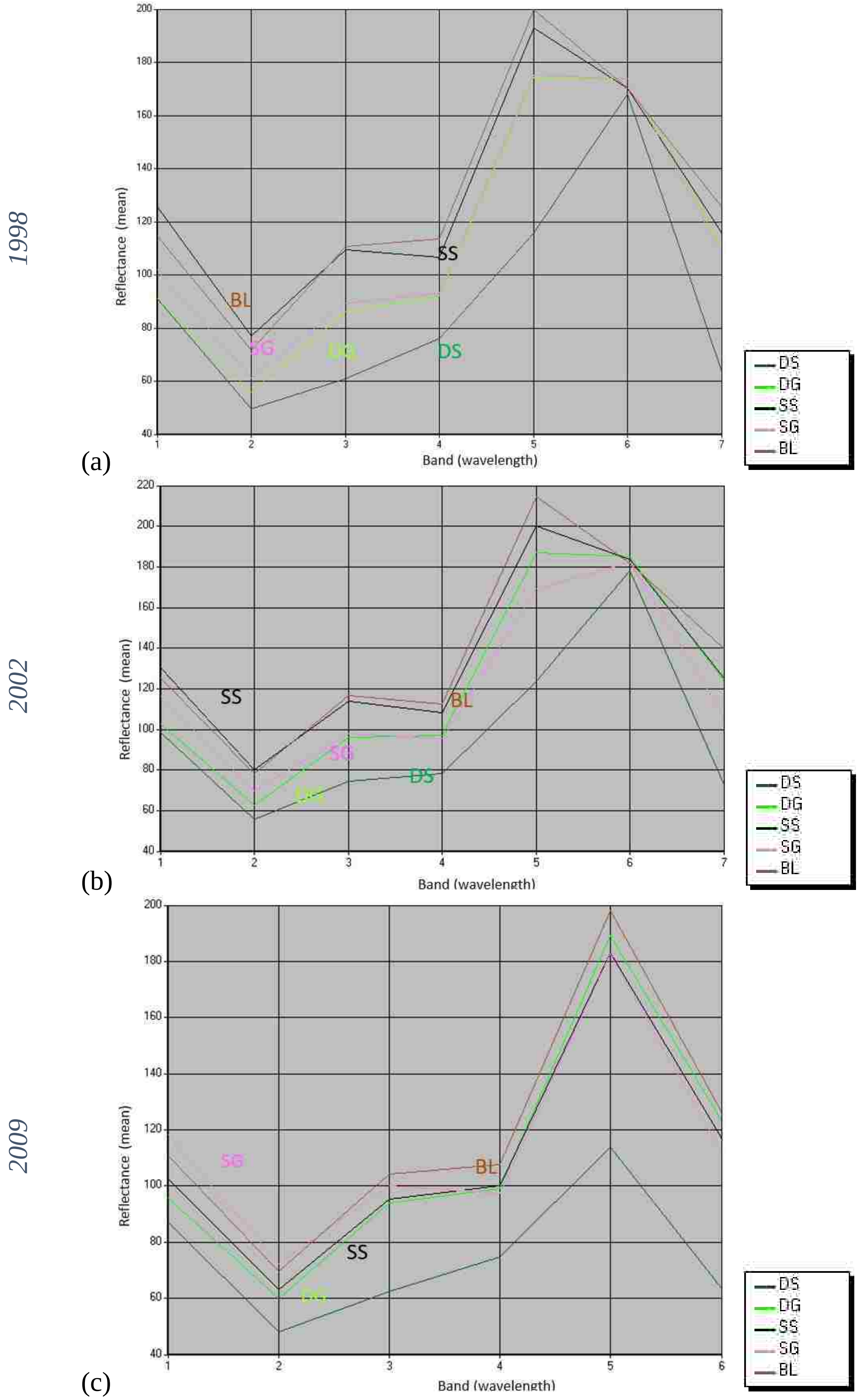


Figure 10. Mean spectral curves for all selected spectra (DS, DG, SS, SG, & BL) in 1998, 2002, ad 2009.

Table 1. Monthly precipitation (mm) data for during the ten-year drought period

| | **1997** | **1998** | **2001** | **2002** | **2008** | **2009** | **2010** |
|---|---|---|---|---|---|---|---|
| **Jan** | 24.6 | 10.4 | 16.3 | 1.8 | 38.9 | 10.2 | 53.3 |
| **Feb** | 6.1 | 24.1 | 10.4 | 0.0 | 21.6 | 5.1 | 15.2 |
| **Mar** | 0 | 22.6 | 13 | 0.0 | 0 | 5.1 | 25.4 |
| **Apr** | 44.7 | 9.9 | 8.4 | 7.6 | 3.6 | 5.1 | 7.6 |
| **May** | 9.1 | 0.0 | 7.4 | 0.0 | 7.9 | 22.9 | 7.6 |
| **Jun** | 13.2 | 0.0 | 4.6 | 0.0 | 6.6 | 2.5 | 2.5 |
| **Jul** | 22.1 | 59.2 | 20.8 | 19.6 | 39.6 | 20.3 | 35.6 |
| **Aug** | 59.2 | 14.0 | 32.5 | 19.3 | 18 | 0.0 | 50.8 |
| **Sep** | 36.6 | 10.4 | 1 | 39.6 | 17.5 | 7.6 | 20.3 |
| **Oct** | 34 | 68.3 | 0.8 | 15.5 | 11.7 | 7.6 | 30.5 |
| **Nov** | 9.7 | 20.1 | 5.8 | 9.4 | 13 | 2.5 | 0.0 |
| **Dec** | 6.9 | 5.3 | 18 | 13.0 | 29.5 | 12.7 | 15.2 |
| ***Monthly Avg.*** | 22.2 | 20.3 | 11.6 | 10.5 | 17.3 | 8.5 | 22.0 |

Table 2. Total livestock count for 1998, 2000, and 2003 from Navajo Nation Department of Water Resources.

| 1998 | Sheep units conversion factor | No. of animals (1998) | Sheep unit equivalents |
|---|---|---|---|
| Sheep: | x 1 | 3,333 | **3,333** |
| Goats: | x 1 | 527 | **527** |
| Cattle: | x 4 | 981 | **3,924** |
| Horses/ Burros: | x 5 | 341 | **1,705** |
| | | 5,182 | **10,470** |

| 2000 | Sheep units conversion factor | No. of animals (2000) | Sheep unit equivalents |
|---|---|---|---|
| Sheep: | x 1 | 3,453 | **3,453** |
| Goats: | x 1 | 303 | **303** |
| Cattle: | x 4 | 528 | **2,112** |
| Horses/ Burros: | x 5 | 253 | **1,265** |
| | | 4,537 | **7,661** |

| 2003 | Sheep units conversion factor | No. of animals (2003) | Sheep unit equivalents |
|---|---|---|---|
| Sheep: | x 1 | 1,338 | **1,338** |
| Goats: | x 1 | 536 | **536** |
| Cattle: | x 4 | 341 | **1,364** |
| Horses/ Burros: | x 5 | 188 | **940** |
| | | 2,403 | **4,178** |

Table 3. Selection of Landsat Imagery dates

| ***No*** | **Satellite** | **Resolution** | **Year** | **Path/ Row** | **Date** | **Month** |
|---|---|---|---|---|---|---|
| ***1*** | Landsat 5 TM | 30 m | 1998 | 36/35 | 5 | August |
| ***2*** | Landsat 5 TM | 30 m | 2002 | 36/35 | 16 | August |
| ***3*** | Landsat 5 TM | 30 m | 2009 | 36/35 | 19 | August |

Table 4. Calibration and validation (sites) points derived from Google Earth observations for 1998, 2002 and 2009 using a 5 x 5 grid dot-matrix.

| **Class** | **Landcover scheme** | **Description** | **Abrv.** | **Sites** |
|---|---|---|---|---|
| *1* | Dense Shrub | Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically GREATER than 60% of total vegetation | DS | 120 |
| *2* | Dense Grassland | Areas dominated by herbaceous vegetation, generally GREATER than 60% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing. | DG | 120 |
| *3* | Sparse Shrub | Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically LESS than 60% of total vegetation | SS | 120 |
| *4* | Sparse Grassland | Areas dominated by herbaceous vegetation, generally LESS than 60% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing. | SG | 120 |
| *5* | Barren Land | Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover. | BL | 120 |

Table 5. Change in Vegetation from NDVI for 1998 to 2009.

| | 1998 | | 2002 | | relative change | |
|---|---|---|---|---|---|---|
| **Land cover** | **Pixel #** | **Area (km2)** | **Pixel #** | **Area (km2)** | **Pixel #** | **Area (km2)** |
| **Veg** | 442953 | 398.7 | 200646 | 180.6 | -242307 | -218.08 |

| | 2002 | | 2009 | | relative change | |
|---|---|---|---|---|---|---|
| **Land cover** | **Pixel #** | **Area (km2)** | **Pixel #** | **Area (km2)** | **Pixel #** | **Area (km2)** |
| **Veg** | 200646 | 180.6 | 408611 | 367.7 | 207965 | 187.17 |

Table 6. Summary of land cover changes from 1998 to 2002 and from 2002 to 2009. Red highlights are decreasing numbers from year to year.

| | 1998 | | 2002 | | relative change | |
|---|---|---|---|---|---|---|
| **Land cover** | **km$^2$** | **%** | **km$^2$** | **%** | **km$^2$** | **%** |
| **DS** | 17 | 3.2 | 20 | 3.8 | 3 | 0.5 |
| **DG** | 48 | 8.9 | 111 | 20.5 | 62 | 11.6 |
| **SS** | 34 | 6.3 | 32 | 5.8 | -3 | -0.5 |
| **SG** | 174 | 32.2 | 34 | 6.4 | -140 | -25.8 |
| **BL** | 263 | 48.5 | 341 | 63.1 | 79 | 14.6 |
| **Total** | 536 | 99 | 539 | 100 | 0 | 0.5 |

| | 2002 | | 2009 | | relative change | |
|---|---|---|---|---|---|---|
| **Land cover** | **km$^2$** | **%** | **km$^2$** | **%** | **km$^2$** | **%** |
| **DS** | 20 | 3.8 | 122 | 22.6 | 102 | 18.9 |
| **DG** | 111 | 20.5 | 77 | 14.2 | -34 | -6.3 |
| **SS** | 32 | 5.8 | 69 | 12.7 | 37 | 6.8 |
| **SG** | 34 | 6.4 | 61 | 11.2 | 26 | 4.8 |
| **BL** | 341 | 63.1 | 211 | 38.9 | -131 | -24.2 |
| **Total** | 539 | 100 | 539 | 100 | 0 | 0 |

Table 7. Supervised (Maximum Likelihood) Classification and Accuracy Assessment for 1998, 2002 and 2009, using image reference points. Diagonals represent sites classified correctly according to ground reference data. Off-diagonals represent misclassified.

| **1998** | | **IMAGE reference** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Class** | **1** | **2** | **3** | **4** | **5** | **Total** | **Users** |
| **CLASSIFIED IMAGE** | **1** | 20 | 0 | 0 | 0 | 0 | 20 | **100%** |
| | **2** | 0 | 17 | 0 | 0 | 0 | 17 | **100%** |
| | **3** | 0 | 0 | 20 | 0 | 1 | 21 | **100%** |
| | **4** | 0 | 1 | 0 | 18 | 3 | 22 | **80%** |
| | **5** | 0 | 2 | 0 | 2 | 16 | 20 | **80%** |
| | **Total** | 20 | 20 | 20 | 20 | 20 | 100 | |
| | **Producer** | **100%** | **90%** | **100%** | **90%** | **80%** | | **91%** |

| **2002** | | **IMAGE reference** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Class** | **1** | **2** | **3** | **4** | **5** | **Total** | **Users** |
| **CLASSIFIED IMAGE** | **1** | 20 | 0 | 0 | 0 | 2 | 22 | **90%** |
| | **2** | 0 | 18 | 0 | 0 | 0 | 18 | **100%** |
| | **3** | 0 | 0 | 15 | 0 | 1 | 16 | **90%** |
| | **4** | 0 | 1 | 0 | 20 | 0 | 21 | **100%** |
| | **5** | 0 | 1 | 5 | 0 | 17 | 23 | **70%** |
| | **Total** | 20 | 20 | 20 | 20 | 20 | 100 | |
| | **Producer** | **100%** | **90%** | **80%** | **100%** | **90%** | | **90%** |

| **2009** | | **IMAGE reference** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Class** | **1** | **2** | **3** | **4** | **5** | **Total** | **Users** |
| **CLASSIFIED IMAGE** | **1** | 20 | 2 | 0 | 0 | 0 | 20 | **100%** |
| | **2** | 0 | 19 | 4 | 0 | 0 | 23 | **100%** |
| | **3** | 0 | 1 | 15 | 1 | 0 | 17 | **80%** |
| | **4** | 0 | 0 | 1 | 19 | 0 | 20 | **100%** |
| | **5** | 0 | 0 | 0 | 0 | 20 | 20 | **100%** |
| | **Total** | 20 | 20 | 20 | 20 | 20 | 100 | |
| | **Producer** | **100%** | **100%** | **80%** | **100%** | **100%** | | **93%** |

# References

Abd El-Kawy, O. R., Rød, J. K., Ismail, H. A., & Suliman, A. S. (2011). Land use and land cover change detection in the western Nile delta of Egypt using remote sensing data. *Applied Geography*, *31*(2), 483–494.

Adamo, S. B., & Crews-Meyer, K. A. (2006). Aridity and desertification: Exploring environmental hazards in Jáchal, Argentina. *Applied Geography*, *26*(1), 61–85.

Adler, G. (1976, July 8). Klagetoh and wide ruins chapters sponsor horse roundup. *Navajo Times*.

Akbari, M., Mamanpoush, A. r., Gieske, A., Miranzadeh, M., Torabi, M., & Salemi, H. R. (2006). Crop and land cover classification in Iran using Landsat 7 imagery. *International Journal of Remote Sensing*, *27*(19), 4117–4135.

Alrababah, M. A., & Alhamad, M. N. (2006). Land use/cover classification of arid and semi-arid Mediterranean landscapes using Landsat ETM. *International Journal of Remote Sensing*, *27*(13), 2703–2718.

Anderson, J. R. (1976). *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*. U.S. Government Printing Office.

Andreadis, K. M., & Lettenmaier, D. P. (2006). Trends in 20th century drought over the continental United States: U.S. *Geophysical Research Letters*, *33*(10).

Bailey, G., & Bailey, R. G. (1986). *A History of the Navajos* (2nd ed.). Santa Fe, N.M.: School of American Research Press.

Bakr, N., Weindorf, D. C., Bahnassy, M. H., Marei, S. M., & El-Badawi, M. M. (2010). Monitoring land cover changes in a newly reclaimed area of Egypt using multi-temporal Landsat data. *Applied Geography*, *30*(4), 592–605.

Banskota, A., Kayastha, N., Falkowski, M. J., Wulder, M. A., Froese, R. E., & White, J. C. (2014). Forest Monitoring Using Landsat Time Series Data: A Review. *Canadian Journal of Remote Sensing*, *40*(5), 362–384.

Beatley, J. C. (1974). Phenological Events and Their Environmental Triggers in Mojave Desert Ecosystems. *Ecology*, *55*(4), 856–863.

Belsky, A. J. (1987). The Effects of Grazing: Confounding of Ecosystem, Community, and Organism Scales. *The American Naturalist*, *129*(5), 777–783.

Belsky, A. J., Matzke, A., & Uselman, S. (1999). Survey of livestock influences on stream and riparian ecosystems in the western United States. *Journal of Soil and Water Conservation*, *54*(1), 419+.

Biondini, M. E., Patton, B. D., & Nyren, P. E. (1998). Grazing Intensity and Ecosystem Processes in a Northern Mixed-Grass Prairie, USA. *Ecological Applications*, *8*(2), 469.

Birtwistle, A. N., Laituri, M., Bledsoe, B., & Friedman, J. M. (2016). Using NDVI to measure precipitation in semi-arid landscapes. *Journal of Arid Environments*, *131*, 15–24.

Bitsoi, A. (2013). Experts say Navajos must confront long-term drought.

Bork, E. W., West, N. E., & Walker, J. W. (1998). Cover Components on Long-Term Seasonal Sheep Grazing Treatments in Three-Tip Sagebrush Steppe. *Journal of Range Management*, *51*(3), 293.

Bradley, B. A., & O'Sullivan, M. T. (2011). Assessing the short-term impacts of changing grazing regime at the landscape scale with remote sensing. *International Journal of Remote Sensing*, *32*(20), 5797–5813.

Brown, A. L. (1950). Shrub invasion of southern Arizona desert grassland. *Journal of Range Management*, 172–177.

Brown, J. H., & McDonald, W. (1995). Livestock grazing and conservation on southwestern rangelands. *Conservation Biology*, *9*(6), 1644–1647.

Bruce, J. P. (1994). Natural disaster reduction and global change. *Bulletin of the American Meteorological Society*, *75*(10), 1831–1835.

Chen, Z. M., Babiker, I. S., Chen, Z. X., Komaki, K., Mohamed, M. A. A., & Kato, K. (2004). Estimation of interannual variation in productivity of global vegetation using NDVI data. *International Journal of Remote Sensing*, *25*(16), 3139–3159.

Cohen, W. B., & Goward, S. N. (2004). Landsat's role in ecological applications of remote sensing. *Bioscience*, *54*(6), 535–545.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*(1), 35–46.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. W. (2004). Long-Term Aridity Changes in the Western United States. *Science*, *306*(5698), 1015–1018.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., & Lambin, E. (2004). Review Article Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing*, *25*(9), 1565–1596.

Dai, A., Trenberth, K. E., & Qian, T. (2004). A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology, 5*(6), 1117–1130.

Dewidar, K. M. (2004). Detection of land use/land cover changes for the northern part of the Nile delta (Burullus region), Egypt. *International Journal of Remote Sensing*, *25*(20), 4079–4089.

Dick-Peddie, W. A., Moir, W. H., & Spellenberg, R. (2000). *New Mexico vegetation: past, present, and future.* University of New Mexico Press.

Diouf, A., & Lambin, E. F. (2001). Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. *Journal of Arid Environments*, *48*(2), 129–148.

Draut, A. E., Redsteer, M. H., & Amoroso, L. (2012a). Recent Seasonal Variations in Arid Landscape Cover and Aeolian Sand Mobility, Navajo Nation, Southwestern United States. *American Geophysical Union*, (198), 51–62.

Draut, A. E., Redsteer, M. H., & Amoroso, L. (2012b). Vegetation, substrate, and eolian sediment transport at Teesto Wash, Navajo Nation, 2009-2012.

Eklundh, L., Harrie, L., & Kuusk, A. (2001). Investigating relationships between Landsat ETM+ sensor data and leaf area index in a boreal conifer forest. *Remote Sensing of Environment*, *78*(3), 239–251.

Fadhil, A. M. (2011). Drought mapping using Geoinformation technology for some sites in the Iraqi Kurdistan region. *International Journal of Digital Earth*, *4*(3), 239–257.

Fairhead, J., Leach, M., & Millimouno, D. (2011). *Misreading the African landscape : society and ecology in a forest-savanna mosaic* (Reissued.). Cambridge : Cambridge University Press,.

Floyd, M. L, Fleischner, T. L., Hanna, D., & Whitefield, P. (2003). Effects of Historic Livestock Grazing on Vegetation at Chaco Culture National Historic Park, New Mexico. *Onservation Biology*, *17*, 1703–1711.

Folger, P., Cody, B. A., & Carter, N. T. (2012). Drought in the United States: Causes and issues for Congress. Congressional Research Service, Library of Congress.

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, *80*(1), 185–201.

Gandhi, G. M., Parthiban, S., Thummalu, N., & Christy, A. (2015). Ndvi: Vegetation Change Detection Using Remote Sensing and Gis – A Case Study of Vellore District. *3rd International Conference on Recent Trends in Computing 2015 (ICRTC-2015)*, *57*, 1199–1210.

Gao, J., & Liu, Y. (2010). Determination of land degradation causes in Tongyu County, Northeast China via land cover change detection. *International Journal of Applied Earth Observation and Geoinformation*, *12*(1), 9–16.

Gregory, H. E. (1917). *Geology of the Navajo Country: A Reconnaissance of Parts of Arizona, New Mexico, and Utah*. Washington, Government Printing Office.

Hagman, G. (1984). *Prevention Better Than Cure: Report on Human and Natural Disasters in the Third World* (2nd ed.). Stockholm: Swedish Red Cross.

Harniss, R. O., & Wright, H. A. (1982). Summer Grazing of Sagebrush-Grass Range by Sheep. *Journal of Range Management*, *35*(1), 13.

Holden, C. E., & Woodcock, C. E. (2016). An analysis of Landsat 7 and Landsat 8 underflight data and the implications for time series investigations. *Remote Sensing of Environment*.

Horler, D. N. H., & Ahern, F. J. (1986). Forestry information content of Thematic Mapper data. *International Journal of Remote Sensing, 7*(3), 405–428.

Hosseinizadeh, A., SeyedKaboli, H., Zareie, H., Akhondali, A., & Farjad, B. (2015). Impact of climate change on the severity, duration, and frequency of drought in a semi-arid agricultural basin. *Geoenvironmental Disasters, 2*(1).

Huntley, B., & Baxter, R. (2005). *Vegetation ecology and global change, in Vegetation Ecology*. Malden, MA: Blackwell Pub.

Keener, V. (2013). *Climate change and pacific islands: indicators and impacts: report for the 2012 pacific islands regional climate assessment*. Island press.

Kogan, F. N. (1997). Global drought watch from space. *Bulletin of the American Meteorological Society, 78*(4), 621–636.

Kuznar, L. A. (2001). Ecological mutualism in Navajo corrals: Implications for Navajo environmental perceptions and human/plant coevolution. *Journal of Anthropological Research*, 17–39.

Lang, R., Shao, G., Pijanowski, B. C., & Farnsworth, R. L. (2008). Optimizing unsupervised classifications of remotely sensed imagery with a data-assisted labeling approach. *Computers & Geosciences, 34*(12), 1877–1885.

Lauer, D. T., Morain, S. A., & Salomonson, V. V. (1997). The Landsat program: Its origins, evolution, and impacts. *Photogrammetric Engineering and Remote Sensing, 63*(7), 831–838.

Le Comte, D. (1994). Weather highlights around the world. *Weatherwise, 47*, 23–26.

Le Comte, D. (1995). Weather highlights around the world. *Weatherwise, 48*, 20–22.

Lin, P.-L., & Brunsell, N. (2013). Assessing Regional Climate and Local Landcover Impacts on Vegetation with Remote Sensing. *Remote Sensing, 5*(9), 4347–4369.

Lloyd-Hughes, B., & Saunders, M. A. (2002). A drought climatology for Europe. *International Journal of Climatology, 22*(13), 1571–1592.

Loveland, T. R., Zhu, Z., Ohlen, D. O., & Yang, L. (1999). An Analysis of IGBP Global Land-Cover Characterization Process. *Photogrammetric Engineering and Remote Sensing*, *65*(9), 1069–1074.

Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*(12), 2365–2401.

Lunetta, R. S., & Elvidge, C. (1998). *Remote sensing change detection : environmental monitoring methods and applications*. Chelsea, Mich. : Ann Arbor Press.

Maarel, E. van der (Ed.). (2005). *Vegetation ecology*. Malden, MA: Blackwell Pub.

Manier, D. J., & Hobbs, N. T. (2007). Large herbivores in sagebrush steppe ecosystems: livestock and wild ungulates influence structure and function. *Oecologia*, *152*(4), 739–750.

Markham, B. L., Storey, J. C., Williams, D. L., & Irons, J. R. (2004). Landsat sensor performance: history and current status. *IEEE Transactions on Geoscience and Remote Sensing*, *42*(12), 2691–2694.

Mas, J. F. (1999). Monitoring land-cover changes: A comparison of change detection techniques. *International Journal of Remote Sensing*, *20*(1), 139–152.

Mayes, V. O., Lacy, B. B., Ahasteen, J., & Chee, J. (1989). *Nanise' : a Navajo herbal : one hundred plants from the Navajo Reservation*. Tsaile, Arizona: Navajo Community College Press.

Mei, A., Manzo, C., Fontinovo, G., Bassani, C., Allegrini, A., & Petracchini, F. (2015). Assessment of land cover changes in Lampedusa Island (Italy) using Landsat TM and OLI data. *Journal of African Earth Sciences*.

Meyer, S. J., Riebsame, W. E., Changnon, S. A., & Karl, T. R. (1992). Review of Drought and Natural Resources Management in the United States: Impacts and Implications of the 1987-89 Drought. *Great Plains: A Journal of Natural and Social Sciences*.

Milchunas, D. G., & Lauenroth, W. K. (1993). Quantitative Effects of Grazing on Vegetation and Soils Over a Global Range of Environments. *Ecological Monographs*, *63*(4), 327–366.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1–2), 202–216.

Mitchell, J. G. (2002). Down the Drain? The Incredible Shrinking Great Lakes, National. *National Geographic*, 37–51.

Obasi, G. O. P. (1994). WMO’s Role in the International Decade for Natural Disaster Reduction. *American Meteorological Society*, *75*(9), 1655–1661.

O’Connor, T. G., & Pickett, G. A. (1992). The Influence of Grazing on Seed Production and Seed Banks of Some African Savanna Grasslands. *The Journal of Applied Ecology*, *29*(1), 247.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., … others. (2014). *Climate change 2014: synthesis Report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change*. IPCC.

Palmer, W. C. (1965). Meteorological Drought. *Research Paper No. 45. U.S. Weather Bureau*.

Panu, U. S., & Sharma, T. C. (2002). Challenges in drought research: some perspectives and future directions. *Hydrological Sciences Journal*, *47*(S1), S19–S30.

Parman, D. L. (1976). *The Navajos and the New Deal*. New Haven : Yale University Press,.

Pickett, S. T. ., & Cadenasso, M. L. (2005). *Vegetation Dynamics, in Vegetation Ecology*. Malden, MA: Blackwell Pub.

Redsteer, M. H., Kelley, K. B., Francis, H., & Block, D. (2012). Disaster Risk Assessment Case Study: Recent drought on the Navajo Nation, southwestern Unites States. 2011 United Nations Global Assessment Report on Disaster Risk Reduction, annexes and papers.

Reed, B. C., Brown, J. F., VanderZee, D., Loveland, T. R., Merchant, J. W., & Ohlen, D. O. (1994). Measuring phenological variability from satellite imagery. *Journal of Vegetation Science*, *5*(5), 703–714.

Roessel, R., & Johnson, B. H. (1974). *Navajo Livestock Reduction: A National Disgrace* (1st ed.). Chinle, Arizona: Navajo Community College Press.

Ross, T., & Lott, N. (2000). *A Climatology of Recent Extreme Weather and Climate Events* (No. 2000-02). Asheville, North Carolina: National Climatic Data Center.

Roy, D. P., Kovalskyy, V., Zhang, H. K., Vermote, E. F., Yan, L., Kumar, S. S., & Egorov, A. (2016). Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sensing of Environment*.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A., & Whitford, W. G. (1990). Biological feedbacks in global desertification. *Science*, *247*(4946), 1043–1048.

Schulz, J. J., Cayuela, L., Echeverria, C., Salas, J., & Rey Benayas, J. M. (2010). Monitoring land cover change of the dryland forest landscape of Central Chile (1975–2008). *Applied Geography*, *30*(3), 436–447.

Schuman, G. E., Reeder, J. D., Manley, J. T., Hart, R. H., & Manley, W. A. (1999). Impact of Grazing Management on the Carbon and Nitrogen Balance of a Mixed-Grass Rangeland. *Ecological Applications*, *9*(1), 65.

Schwinning, S., & Sala, O. E. (2004). Hierarchy of responses to resource pulses in arid and semi-arid ecosystems. *Oecologia*, *141*(2), 211–220.

Seager, R. (2007). The Turn of the Century North American Drought: Global Context, Dynamics, and Past Analogs. *Journal of Climate*, *20*(22), 5527–5552.

Senf, C., Leitão, P. J., Pflugmacher, D., van der Linden, S., & Hostert, P. (2015). Mapping land cover in complex Mediterranean landscapes using Landsat: Improved classification accuracies from integrating multi-seasonal and synthetic imagery. *Remote Sensing of Environment*, *156*, 527–536.

Shalaby, A., & Tateishi, R. (2007). Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. *Applied Geography*, *27*(1), 28–41.

Sierra-Soler, A., Adamowski, J., Malard, J., Qi, Z., Saadat, H., & Pingale, S. (2016). Assessing agricultural drought at a regional scale using LULC classification, SPI, and vegetation indices: case study in a rainfed agro-ecosystem in Central Mexico. *Geomatics, Natural Hazards and Risk*, *7*(4), 1460–1488.

Singh, A. (1989). Review Article Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing*, *10*(6), 989–1003.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., … Stephens, S. (2002). The Drought Monitor. *Bulletin of the American Meteorological Society*, *83*(8), 1181–1190.

Szinell, C. S., Bussay, A., & Szentimrey, T. (1998). Drought Tendencies in Hungary. *International Journal of Climatology*, *18*, 1479–1491.

Tannehill, I. R. (1949). DROUGHT-ITS CAUSES AND EFFECTS. *Journal of the South African Forestry Association*, *18*(1), 83–84.

Thomas, K. A., & Redsteer, M. H. (2016). Vegetation of semi-stable rangeland dunes of the Navajo Nation, Southwestern USA. *Arid Land Research and Management*, *30*(4), 400–411.

USGS. (2014). EarthExplorer. http://earthexplorer.usgs.gov/

van der Schrier, G., Efthymiadis, D., Briffa, K. R., & Jones, P. D. (2007). European Alpine moisture variability for 1800–2003. *International Journal of Climatology*, *27*(4), 415–427.

Vanderpost, C., Ringrose, S., Matheson, W., & Arntzen, J. (2011). Satellite based long-term assessment of rangeland condition in semi-arid areas: An example from Botswana. *Journal of Arid Environments*, *75*(4), 383–389.

Vicente-Serrano, S. M. (2007). Evaluating the Impact of Drought Using Remote Sensing in a Mediterranean, Semi-arid Region. *Natural Hazards*, *40*(1), 173–208.

Vorovencii, I. (2014). Assessment of some remote sensing techniques used to detect land use/land cover changes in South-East Transilvania, Romania. *Environmental Monitoring and Assessment*, *186*(5), 2685–2699.

Washington-Allen, R. A., West, N. E., Ramsey, R. D., & Efroymson, R. A. (2006). A Protocol for Retrospective Remote Sensing–Based Ecological Monitoring of Rangelands. *Rangeland Ecology & Management*, *59*(1), 19–29.

Weber, G. E., Jeltsch, F., Van Rooyen, N., & Milton, S. J. (1998). Simulated long-term vegetation response to grazing heterogeneity in semi-arid rangelands. *Journal of Applied Ecology*, 687–699.

Weisiger, M. (2007). Gendered Injustice: Navajo Livestock Reduction in the New Deal Era. *The Western Historical Quarterly*, *38*(4), 437.

Weisiger, M. L., & Cronon, W. (2009). *Dreaming of Sheep in Navajo Country*. University of Washington Press, Seattle, WA: Weyerhaeuser environmental books.

Weiss, J. L., Castro, C. L., & Overpeck, J. T. (2009). Distinguishing Pronounced Droughts in the Southwestern United States: Seasonality and Effects of Warmer Temperatures. *Journal of Climate, 22*(22), 5918–5932.

Weiss, J. L., Gutzler, D. S., Allred Coonrod, J. E., & Dahm, C. N. (2004). Seasonal and inter-annual relationships between vegetation and climate in central New Mexico, USA. *Journal of Arid Environments*, *57*(4), 507–534.

Weiss, J. L., Gutzler, D. S., Coonrod, J. E. A., & Dahm, C. N. (2004). Long-term vegetation monitoring with NDVI in a diverse semi-arid setting, central New Mexico, USA. *Journal of Arid Environments*, *58*(2), 249–272.

Westerling, A. L. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*, *313*(5789), 940–943.

White, R. (1988). *The Roots of Dependency : Subsistence, Environment, and Social Change Among the Choctaws, Pawnees, and Navajos* (Vol. [1st pbk. ed., 1988]). Lincoln, Neb: University of Nebraska Press.

Wilhite, D. A. (2000). *Chapter 1 Drought as a natural hazard: concepts and definitions* (Vols. 1–1). London: Routledge: Drought: A Global Assessment.

Wilhite, D. A., & Glantz, M. H. (1985). Understanding the drought phenomenon: the role of definitions. *Water International, 10*(3).

Wilhite, D. A., Sivakumar, M. V. K., & Pulwarty, R. (2014). Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, *3*, 4–13.

Yang, W., Yang, L., & Merchant, J. W. (1997). An assessment of AVHRR/NDVI-ecoclimatological relations in Nebraska, U.S.A. *International Journal of Remote Sensing*, *18*(10), 2161–2180.

Yevjevich, V. M. (1967). An objective approach to definitions and investigations of continental hydrologic droughts. *Hydrology Papers (Colorado State University); No. 23*.

Yuan, F., Sawaya, K. E., Loeffelholz, B. C., & Bauer, M. E. (2005). Land cover classification and change analysis of the Twin Cities (Minnesota) Metropolitan Area by multitemporal Landsat remote sensing. *Remote Sensing of Environment*, *98*(2–3), 317–328.

Yurth, C. (2008). Drought / Ranchers denied relief. *Navajo Times*, pp. A2-3.

Zhou, Q., Li, B., & Chen, Y. (2011). Remote Sensing Change Detection and Process Analysis of Long-Term Land Use Change and Human Impacts. *AMBIO*, *40*(7), 807–818.