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Land Cover Change During a Transition in Land Management at Valles Caldera 1989-2013

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**LAND COVER CHANGE
DURING A TRANSITION IN LAND MANAGEMENT
AT VALLES CALDERA 1989-2013**

by

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B.A. INTERNATIONAL DEVELOPMENT STUDIES
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THESIS

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**LAND COVER CHANGE
DURING A TRANSITION IN LAND MANAGEMENT AT
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ABSTRACT

This study examines how land-use policies can play a role in manifesting physical landscape changes. In 2000, Congress enacted a unique experiment in public lands management by creating the Valles Caldera National Preserve and its governing body, the Valles Caldera Trust (VCT). The management approach enacted by Valles Caldera Trust marked a significant departure in land-use intensity. To assess how these changes in management have affected land-use intensity and resulting cover change, this research seeks to identify landscape-level changes that taken place during a period of ten years prior to and following the formation of the Valles Caldera National Preserve (i.e., 1989-2013).

Remote sensing techniques were used to quantify land cover transitions. Landsat image data (30m) from 1989, 1999, 2003, and 2013 were compared to identify changes that have taken place between the time periods 1989-1999, a period just prior to the purchase of the Baca Ranch by the federal government, and 10 years of management by the Valles Caldera Trust, 2003-2013. In order to do this, pre-classification change detection was used to quantify changes that have taken place during each period and a

range of historical evidence used to classify those changes by disturbance regime. Results demonstrate an increase in wetland and rangeland recovery under VCT management based on evaluating several ancillary datasets. This leads to the conclusion that adaptive management strategies were beneficial for these cover types. The impact of the VCT's adaptive management strategies on forests is difficult to understand due to large wildfire-induced cover changes that occurred during VCT management.

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1.0 Introduction

In 2000, approximately 89,000 acre Baca Ranch in northern New Mexico was purchased by the United States government and designated the Valles Caldera National Preserve (VCNP). The rationale for the purchase was that the land contained “significant scientific, cultural, historic, recreational, ecological, wildlife, fisheries, and productive values (Valles Caldera Preservation Act, 2000). One of the caveats of the purchase was that the land was to be governed by a new federal entity, the Valles Caldera Trust (VCT), rather than by one of the traditional federal land agencies, with a renewable mandate until 2020.

In the VCPA several management goals are mandated, including that VCT manage the land with the intention of becoming financially self-sustaining (Valles Caldera Preservation Act 2000). In order to meet this goal, the act provides for the land to be managed for a variety of income-generating activities, such as timber harvesting, cattle ranching, hunting, fishing and recreational use (Valles Caldera Preservation Act, 2000). Despite continuation of resource extraction, VCT’s management goals mark a departure in land-use intensity when compared to the period of private ownership, with logging and livestock grazing practiced at lower intensities than before, and elimination of other uses (e.g., geothermal energy exploration).

VCT adhered to principles of adaptive management, seeking to apply the scientific method to management in order to characterize and guide management activities (Gess 2006). In adaptive management, land management is conducted as an experiment, with results informing future management (Kelly et al. 2012). In addition to public input, the Valles Caldera Preservation Act (VCPA) set up a nine-member board of trustees, with seven members appointed by President of the United States (Gess 2006). The other two members included the Supervisor of the Santa Fe National Forest and the Superintendent of Bandelier National Monument (Valles Caldera Preservation Act). At least five board members were New Mexico residents with ranging interests and expertise and not employees of the federal government (Valles Caldera Preservation Act, 2000). The VCT operated under a special designation within Santa Fe National Forest, is one of only two federal land trusts (Fairfax, Gwin, and Huntsinger 2004), and operates as a “wholly government owned corporation” (Valles Caldera Trust), at the insistence of then-New Mexico Senator Pete Dominici, who supported continuing grazing and hunting at Valles Caldera (Benson, personal correspondence)

Failure to be financially self-sustaining as outlined in the VCPA, led to changes in VCT’s mandate in late 2014 with the passage of the FY 2015 National Defense Authorization Act (FY 2015 NDAA). The law turned management of the preserve to the National Park Service (NPS), which took place in November 2015. By then, was not going to meet the goal of being profitable by the end of FY 2015. According to a Government

Accountability Report published in 2009, the trust was five years behind schedule (Government Accountability Report 2009). The transition of VCNP within the federal land system marks a departure from the experimental private-public partnership structure of VCT. Management aims under the NPS management are similar to S.285, the Valles Caldera National Preserve Management Act, which was introduced by New Mexico Senator Jeff Bingaman in early 2013. Much of the intent of the bill was included in FY 2015 NDAA. Prior to the FY 2015 NDAA, the VCPA stipulated VCT's mandate as extendable until 2020, with transfer to the United States Forest Service under Santa Fe National Forest (Valles Caldera Preservation Act 2000).

Given the unique nature of use, ownership, and management of the VCT, there is a opportunity to assess the impact of the experimental management approach of the VCT in terms of physical impact on the landscape. To do so, multi-temporal remote sensing image data and land cover change analysis was used to identify and measure land cover transitions. By studying patterns and rates of land cover change prior to and following the formation of VCNP, the impact of the change in management approach can be empirically measured in terms of its impact on the physical landscape. Landsat image data from 1989, 1999, 2003, and 2013 was compared to identify changes that have taken place between the time periods 1989-1999, representing a period of 10 years prior to formation of VCNP, and 2003-2013, 10 years of management of the Valles Caldera Trust. Total change was assessed from 1989-2013. In order to do this, pre-

classification change detection was used to quantify changes that have taken place during each period. Historical records, including a 2000 land cover map, logging and fire histories, and historical aerial photography, were used to determine the land cover categories being affected and the likely driver of the change. Identifying areas of change in the landscape will help inform transitioning land management at Valles Caldera in understanding how landscape level changes have manifested during the 24 year period of study and during the transition to federally protected status. This study will help inform NPS land managers as they continue to implement adaptive management at VCNP.

1.1 Research Questions

The objective of the proposed research is to determine the rate of land cover change that has taken place before and after the formation of the VCT. Specifically, this research seeks to answer the following questions:

1. What land cover changes occurred within the ten years of private ownership (1989-1999) prior to the formation of VCNP?
2. What changes have occurred during ten years (2003-2013) of management by VCT?

3. How do the detected transitions differ in magnitude and pattern under the adaptive management regime of the VCT when compared to private management?

1.2 Organization of the Thesis

The background section of this thesis includes an introduction of the physical setting of Valles Caldera with an emphasis on the geology, ecology and climate. The history of human settlement at Valles Caldera is then discussed in terms of the differing roles that human occupation has played in altering land-use. An archeological record shows human occupation by indigenous groups followed by periods of rule by the Spanish, Mexican, and United States governments.. During the period of private ownership (1860-2000), variable extractive use, including livestock grazing, timber harvest, and geothermal exploration occurred within the Caldera. The formation, structure, and management goals of the Valles Caldera Trust are then reviewed.

The second section of the thesis focuses upon efforts to understand how land-use management and land cover are linked. Management-based activities, such as timbering and grazing, can influence the category and condition of cover types and their transitions to different states. An understanding of future land cover in the southwestern United States is briefly discussed as a rationale for the study and the use

of remote sensing for land cover change analysis are reviewed. Following a description of the methods employed in this study, results are presented and discussed, including an examination of the drivers of the observed changes in land cover.

2.0 Background

Despite the recent dissolution of the VCT, its formation marked significant changes to how the Valles Caldera area was managed. There are signs of human occupation at VCNP dating back 10,000 years, but the recent period of private ownership (1860-2000) marked the start of substantial changes in land-use. Extensive timbering and ranching took place, along with geothermal energy exploration that resulted in several wells being drilled during the 20th century. These often intensive land-uses, long periods of overgrazing in particular, continue to have a lasting impact on the on the landscape (Parmenter 2009). Heavy sheep grazing during private ownership is thought to have had long-standing impacts on habitat availability and quality, particularly in the cold-water fishery (Muldavin and Tonne 2003).

2.1 Physical History of Valles Caldera National Preserve

Valles Caldera National Preserve (VCNP) is located in the northern Jemez Mountains, primarily in Sandoval County, with small portions in Rio Arriba and Los Alamos Counties. The large bowl-like formation of the VCNP is punctuated by grassy valleys, or *valles*, and

a rolling landscape with several forested mountain peaks. VCNP is part of the larger Jemez Mountain Volcanic Field (JMVF), commonly called the Jemez Mountains.

2.1.1 Geology

The stratigraphy of the JMVF and Valles Caldera was first identified by Baily et al. 1969 and Smith et al. 1970 (Heiken et al. 1990). The JMVF was formed roughly 15 million years ago during the mid to late Miocene by a series of volcanic eruptions (Goff and Gardner 2004; Dunbar 2010). Elevation in JMVF ranges from 1590 m to 3,525 m at Tschimcoma Peak (Touchan, Allen and Swetnam 1996). The volcanic field is the expression of two converging land features, the northeast trending Jemez Lineament and the north-trending Rio Grande Rift (Goff and Gardner 2004). The Jemez Lineament is part of a larger a series of volcanic craters formed in the Miocene to Holocene, while the rift is part of a larger extension of grabens located throughout the Rocky Mountains continuing south to Chihuahua, Mexico (Goff 2002).

The lineament and rift converge in the JMVF, leading to the formation of Valles Caldera, a resurgent caldera where two large-scale eruptions occurred 1.6 and 1.23 CE, forming successive calderas at the approximate center of the volcanic field (Dunbar 2010). Each of the large-scale eruptions was followed by the subsequent collapse of the magma chamber, forming the present-day Valles Caldera, approximately 12 miles (19.2 KM)

wide and covering some areas of the previous Toledo Caldera (Anschuetz and Merlan 2007). The period following the formation of the caldera was marked by resurgence, contributing to the uplift of Redondo Peak to its current elevation of 11,254 ft (3430 m) and several smaller eruptions forming ring fracture volcanic domes. The last known volcanic activity took place in the SW section of Valles Caldera, with the Banco Bonito flow that took place approximately 40,000 years ago (Valles Caldera Trust). Rock types on mountainsides are ignimbrite and rhyolite with alluvial and lacustrine present on the caldera floor (Smith et al. 1970; Coop and Givnish 2007).

2.1.2 Ecology

The geologic history of VC has resulted in unique composition of ecosystems influenced by the large elevation gradient, with a base elevation of 8,000 ft (915 m) and peak elevation at Redondo Peak's elevation 11,254 ft (3430m). Soils at VC are composed of nutrient-rich millisols below the volcanic domes in the *valles*. The volcanic domes are comprised of a mixture of cryic, clay and inceptic soils along with ash-dominated soils in the SW portion of VCNP (Valles Caldera Trust b).

The montane and subalpine grasslands occupy over 10,000 ha of VCNP occurring between 2575-2700m (Coop and Givnish 2007). The grasslands are an important ecological feature in the southern Rocky Mountains, forming high elevation meadows

associated with higher flora and fauna diversity along with economic opportunities for grazing (Coop and Givinish 2007). Grassland composition is influenced by soil condition and moisture, and physiographic conditions including slope, aspect, and elevation. Several genera of grasses are present at VC including: *Festuca* (fescues), *Danthonia* (oatgrasses), *Muhlenbergia* (muhly), *Deschampsia* (tufted hairgrass), *Poa* (bluegrass), and *Blepharoneuron* (pine drop seed) (Dewar 2011). Grasslands at VCNP have been increasingly been encroached upon by *Picea pungens* (Blue spruce), due to the exclusion of beavers allowing channel incision and livestock grazing resulting in drying conditions in meadows (Bogan et al. 1998). Coop and Givinish estimated an overall decline of grasslands from 11,747 to 9,336 ha between 1935-1996 due to tree invasion (2007).

Forest communities at VCNP vary based on aspect and elevation (Falk et al. 2011). Spruce-fir forests are dominant at higher elevations (2749-3430 m) comprised of *Picea engelmannii* (Engelmann spruce), and *Abies lasiocarpa* var. *arizonica* (corkbark fir) Falk et al. 2011). Forests below 3050 m are comprised of mixed conifers including *Pseudotsuga menziesii* (Douglas-fir), *Abies concolor* (white fir), *Pinus strobiformis* (Southwestern white pine), *Picea pungens* (Colorado blue spruce), *Pinus flexilis* (Limber pine), and *Pinus ponderosa* (ponderosa pine), with occasional patches of *Populus tremuloides* (Quaking aspen), and *Quercus gaembelli* (Gambel oak) in warmer or disturbed spruce-fir areas (Falk et al. 2011). Occasional *Acer glabrum* var. *neomexicana* (Rocky Mountain maple) are also present (Touchan, Allen and Swetnam 1996).

Logging at VC was a prominent activity during 1926-1971, a 99 year timbering lease was signed in 1918 by the Redondo Development Company (Merlan and Anschuetz 2007, Chapter 7). Some areas of VCNP, such as Redondo Border and Banco Bonito were denuded of *Pinus ponderosa*, a preferred timbering species, due to gentle topography where stands were easily exploited (Merlan and Anschuetz 2007, Chapter 7; Martin 2003). Resulting second growth stands of *P. ponderosa* exhibit crowding, known as dog hair thickets, increasing fire danger, limiting infiltration from snow melt, and reducing stream discharge downstream (Parmenter 2009).

There is considerable diversity of species present at VCNP, including over sixty species of mammals including: *Ursus americanus* (black bear) *Cynomys gunnisoni* (Gunnison's prairie dog), *Taxidea taxus* (American badger), *Puma concolor* (mountain lion), *Lynx rufus* (bobcat), *Odocoileus hermionus* (Mule deer).

Of animals present at VCNP *Cervus canadensis* (Wapiti elk) has been particularly successful. The species, although not endemic to the Jemez Mountains, is present in a variety of settings. *Cervus Canadensis* were introduced by the New Mexico Department of Game and Fish in the Jemez Mountains in 1947 following the extirpation of the native sub-species *Cervus canadensis merriami* (Merriam's elk) in the early 20th century.

Following slow rates of population growth, the department introduced an additional 58

head between 1964-1965. The population grew swiftly following the 1977 La Mesa fire that took place in Bandelier National Monument. The La Mesa fire was associated with converting a large area of ponderosa forest to grassland that provided winter forage for elk (Allen 1997). Presently VCT estimates the herd to number somewhere between 2500-3000.

2.1.3 Climate

Climate at VCNP is semi-arid and continental. Mean January high and low temperatures are 3.4 C and -13.5 C and, 24.9 C and 2.7 C in July (Coop and Givinish 2008). Much of the annual precipitation (nearly 30%) of 576mm takes place during monsoonal period occurring between July and August (Coop and Givinish 2008). Climate predictions for the southwest project higher sustained temperatures and increased and intensified droughts, accompanied by more plant stress (Allen 2007; Williams et al 2010).

Climate change is predicted to affect VCNP in several ways, including changes in the onset of seasons (Williams et al 2010) and further alteration of fire regimes (Tillery et al. 2011). Williams et al. (2010) predicts higher elevation areas in the southwest will experience greater warming than lower elevations; resulting in earlier arrival of spring due to less snowpack. Warming temperatures are expected to contribute to drying soil and fuels resulting in larger and more frequent wildfires (Williams et al. 2010) and may

disrupt low minimum temperatures that are thought to maintain the open valley bottoms in the *valles* (Coop and Givinish 2008). Recently, there have been two wildfires at VCNP: the 2011 Las Conchas Wildfire (63.12 Ha) and the 2013 Thompson Ridge Wildfire (9.31 Ha). Some areas burned by Las Conchas were previously burned by earlier wildfires (1977 La Mesa Fire, 1996 Dome Fire, and 2000 Cerro Grande fire) (Tillerly et al. 2011) and severely burned areas (e.g., Parajito Plateau) experienced significant erosion (Tillerly et al. 2011).

2.2 History of Human Settlement and Land-use

One of the rationales for the purchase and formation of VCNP was the land's wealth of cultural history (Valles Caldera Preservation Act 2000). Valles Caldera is an area that holds cultural significance for indigenous peoples in the area as an area in personal histories and archeological use as hunting grounds and as an obsidian quarry dating to archeological periods. The *valles* experienced significant sheep and cattle grazing following the arrival of the Spanish. The era of private ownership through a Mexican-era land grant, affirmed by the U.S. federal government, led to additional extractive uses during the 20th century, namely geothermal exploration and industrial timber harvesting.

2.2.1 Pre-settlement

Based on the archeological record, the first known human period of human activity at Valles Caldera occurred during the Paleo Indian Period, or approximately, 10000/9500-5500 BCE (Anschuetz 2007). This era at VC was marked by nomadic large-game hunting of now-extinct bison (*Bison antiquus*), and mammoth (*Mammuthus jeffersonii*) (Anschuetz 2007).

The successive Archaic Period (5500 BCE-600 CE) saw seasonal camps in valleys, meadows and upper dry uplands (Dewar, Thesis 2011). Pueblo Occupation from 600-1600 CE was marked by seasonal hunt camps with activities centered on obsidian quarrying and tool crafting (Anschuetz 2007). Numerous pueblos and indigenous groups maintain a close connection to the land and maintain it as part of their ancestral range (Anschuetz 2007).

The pre-settlement landscape included frequent low-severity fires, likely due to lightning ignitions that maintained ponderosa forest and an open understory consisting of grasses, forbs, and small shrubs (Dewar 2011).

2.2.2 Spanish, Mexican, and US Territorial Periods

Spanish came into the area in 1540 with Coronado's expedition. The Spanish may have identified and started to use Valles Caldera as a cattle and sheep ranching area as soon as 1779 according to a period map of the area (Merlan 2007). Permanent year-round settlement didn't occur in the area until the brief period of Mexican control lasting from 1821 to 1848.

The arrival of Europeans in the Jemez Mountains signaled a departure from historical land-use, particularly in terms of heavy livestock grazing. Pastureland in the *valles* was a sought-after resource that was exploited as the area came under the control of the U.S. Government with the signing of treaty of Guadalupe Hidalgo in 1848. In 1851, a short-lived hay camp was established to provide hay to Santa Fe. The camp was raided by the Diné (Navajo) and abandoned shortly thereafter.

Continuing settlement in the Jemez Mountains profoundly shaped the landscape with the construction of roads and railroads. The Santa Fe Railroad completed a rail line to Albuquerque in 1880. The new rail line enabled rapid growth in ranching, with livestock now able to be shipped to the eastern markets (Elson 1992). The growth of the railroad and ability to access new markets lead to more settlement and facilitated the grazing of larger flocks of sheep in VC (Martin 2003; Coop and Givinsh 2007). By the summers of

1917 and 1918, the estimated sheep flock size at VC was 100,000 (Merlan and Anschuetz 2007). The addition of infrastructure in the Jemez contributed to lower fire disturbance rates as a result of heavy sheep grazing in forests reducing grassy fuels (Allen 2001). Grazing profoundly shaped the landscape of the Jemez, largely through increased fragmentation of surface fuels (Allen 2007), while facilitating further settlement and the addition of infrastructure into a once remote area.

2.2.3 Baca Location No.1

Private ownership at Valles Caldera came about in 1860 as the United States Congress authorized the break-up of a land grant given by the Mexican government to the heirs of the Luis Mariá Cabeza de Baca family. The family originally held a land grant located in present-day Las Vegas, NM, that had been granted to them by the Mexican government in 1821, but was later found to be conflicting with the Las Vegas land grant of 1835 (Merlan and Anschuetz 2007b). This was eventually confirmed after court-ordered surveying of the original land grants; which resulted in the Baca's abandoning their original land claim for equivalent land within the New Mexico Territory. The family chose five 99,289-acre (40.18 ha) plots, with the first location, or Baca Location No. 1 located in Valles Caldera (Merlan and Anschuetz 2007b).

After brief periods of leasing and ownership by the Valles Land Company and the Redondo Development Company, the land was sold in 1918 to George W. and Frank Bond, a family with wool and cattle ranching interests in Northern New Mexico (Merlan and Anschuetz 2007b). A contract signed on December 17, 1918 stipulated the Redondo Development Company retain timbering rights in the form of a 99 year timber lease while the Bonds were to maintain the land's timber resources (Anschuetz and Merlan 2007b). In 1935, Redondo Development Company sold the timbering rights to Firesteel Lumber Company, which promptly entered into an agreement with New Mexico Lumber and Timber Company (Anschuetz and Merlan 2007b). By 1939, Redondo Development Company had deeded all the timbering rights to New Mexico Lumber and Timber Company (Anschuetz and Merlan 2007b).

Widespread timbering and ranching continued at VC after the Bond family sold the land in 1963 to Patrick Dunigan of Abilene, Texas. The Bond family had diversified the grazing to include cattle as well as sheep. By 1950, they were grazing 30,000 sheep and 5,000 cattle (Martin 2003). Dunigan primarily used the land for cattle ranching and geothermal extraction. Dunigan drilled several geothermal energy test wells that proved unprofitable. More intensive timber harvest by the New Mexico Timber Company was spurred on by a change in the definition of harvestable trees by the State of New Mexico in 1962. Under the new regulations, trees as small as 12.5 cm in diameter could be cut, far smaller than the earlier regulation of 30 cm in diameter (Anschuetz and

Merlan 2007b). These changes to regulations, along with the new method of cable logging necessitating a vast network of roads, spurred several lawsuits filed by Dunigan, starting in 1964. By the time Dunigan purchased the timbering rights from New Mexico Timber Company in July 1972, the company had created a network of over 1,000 miles of road, and harvested most of the forested areas (Anschuetz and Merlan 2007b). Of the estimated 26,305 ha of timber harvested, nearly 16,187 ha was removed between 1930-2000 (Muldavin and Tonne 2003).

The Baca cooperative geothermal demonstration project, a cooperative agreement between the US Department of Energy, Union Oil Company, and the Public Service Company of New Mexico began in 1978 and yielded a 20 Megawatt electrical resource (MWe), far below the speculated 400 MWe (Goff 2002). Under Dunigan's ownership, the land was designated a National Natural Landmark by the National Park Service, primarily due to its geologic history (Martin 2003). Negotiations to purchase the land commenced in the 1990's following Dunigan's death in 1980; the US government purchased the land in 2000 with the passage of the Valles Caldera Preservation Act. The act authorized the purchase of the 38348 ha plot for \$101,000,000 from the Land and Water Conservation Fund (Valles Caldera Preservation Act 2000).

2.3 Valles Caldera Trust

Passage of the Valles Caldera Preservation Act (VCPA) created the Valles Caldera Trust to oversee the preserve and to: “preserve the scientific, scenic geological, watershed, fish, wildlife, historic, cultural, and recreational values of the Preserve,” while providing for multiple use and sustained yield of resources (Valles Caldera Preservation Act 2000:114 STAT. 599). Following a two-year study period after purchase by the Forest Service, management was formally transferred to the VCT in August of 2002.

The VCPA established the norms of operation for the VCT, “to establish a demonstration area for an experimental management regime adapted for this unique property which incorporates elements of public and private administration in order to promote long term financial sustainability” (Valles Caldera Preservation Act 2000:114 STAT. 599). As the first federal charter forest, the VCT described itself as “an experiment in public lands management” (Little, Berrens and Champ 2005, 43). A charter forest is a distinctive unit of public land operating outside of federal management agencies with alternative funding, enacted to increase local control while retaining public ownership (Little, Berrens and Champ 2005).

The governing structure of the VCT makes it a novel experiment in managing public land. A nine-member board of trustees manages the VCT. Two the members are currently employees of the federal government; the supervisor of Santa Fe National Forest and the Superintendent of Bandelier National Monument. The remaining board members are appointed by the President of the United States and have expertise in the following areas: domesticated livestock management, management of fish, wildlife, recreation, sustainable management of forest lands, nonprofit conservation activities, financial management, cultural and natural history of the region, and state or local government activities.

The VCT uses adaptive management principles to inform its decision-making. The approach, described by Holling (1978), frames natural resource management as a learning process that decreases uncertainty over time. Adaptive management is well suited for land management where uncertainty and nonlinear interactions can occur (Allen and Gunderson 2011), but is often practiced in contentious management contexts where public lands have diverse stakeholders (Allen and Gunderson 2011, Kelly et al. 2012). Ideally, management is conducted as an iterative experiment, with a tested hypothesis generated around uncertainties and outcomes informing future management goals over time. Kelly et al. (2012) identify five steps to the adaptive management process: 1) Determine management goals, 2) Identify or produce a model based on the ecosystem to predict what the likely outcomes are from the management

goals, 3) Implement management with an experimental design, 4) Gather data from management outcome, 5) Integrate new knowledge into management models, and 6) Alter management as driven by data and repeat the process.

VCT's goals as an agency, defined by the VCPA, are to provide for: 1) protection of scientific, scenic, historic, and natural values, 2) public recreation, 3) sustained yield of timber and livestock grazing, and 4) integration of public and private administration to promote financial sustainability (Valles Caldera Trust, 2012).

Agency goals, along with adaptive management, can be tied to the variety of activities undertaken by VCT that may have affected cover change including livestock grazing and forest management. Livestock operations that were conducted by the VCT included seasonal ranching from late-May until late September. Stocking numbers were determined by range conditions assessed by VCT staff, university biologists, and volunteers, with the expressed goal to preserve 60% of above ground biomass for ecosystem services (Haarman 2012). Data generated by principles of adaptive management determined when some activities took place in the preserve. In response to drought-induced range conditions in winter 2005, the 2006 grazing season was canceled (Valles Caldera Trust 2006). VCT-collected data from 2002-2007 indicates an increase in autumnal end-of season biomass and decreasing summer forage utilization during the same period (Parmenter 2016).

Active forest management by VCT was another example of cover-altering activities undertaken. Forest management included the reintroduction of fire and thinning to mitigate previously logged dog hair thickets that presented high-fire risk (Parmenter, Steffen and Allen 2007). Public input in management decisions was invited on the reintroduction of fire with stakeholder input through focus groups made-up of indigenous groups, ranchers, tour operators, local residents and government personnel (Anschuetz and Raish 2010).

2.4 Land Cover Mapping

Land-use and land cover change (LULCC) is an interdisciplinary science concerned with the investigation of how human and biophysical forces shape land-use and, consequently, land cover (IGBP, 2014). Land cover refers to the biophysical characteristics of the earth, while land-use is the purpose of the land from the perspective of humanity. Land cover mapping is a method of depicting the surface of the earth as a spatial unit, often through classification, in which regions of the earth are classified based on measureable attributes (Global Land Cover Facility 2014). Characteristics such as discrete land cover categories may be measured (Lambin, Geist, and Lepers 2003). Changes in land-use factor prominently into the potential for

modifications or changes to land cover. The primary way of measuring land cover change (LCC) is through remote sensing data gathered from airborne and space-borne sensors

Changes in land cover and land-use have important implications for natural resources; affecting water and soil quality, biodiversity, and climate (de Koning et al. 1999). Policies by a government can regulate the pace and pattern of extractive use, in turn determining land-use and cover characteristics (Lambin et al. 2001). Management policies by government drive land-use, affecting land cover ranging from global scales, such as international treaties (Veldkamp and Lambin 2001), to local scales, where designation of forest reserves may change land cover over time (Rudel et al. 2005). Accurate and up to-date land cover information can lead to more effective ecosystem management (Xian, Homer and Fry 2009).

In the Southwestern United States, there are specific needs for understanding of LULCC for the management of resources, such as the relationship between LULCC and hydrologic recharge (Scanlon et al. 2005). An understanding of LULCC is particularly important for arid lands because the rapid cover changes being experienced in many arid climates are not well understood (French et al. 2008). Changes to climate are projected to result in unprecedented stress on southwestern forests driven by increasing temperature leading to a rise in vapor-pressure deficit, ultimately resulting in novel type conversion (Williams et al. 2013).

The era of private ownership at VC included several changes to the landscape through livestock husbandry, logging, fire suppression, geothermal energy exploration, and the introduction of *Cervus canadensis* (Rocky Mountain Elk) to the Jemez Mountains in 1947. Trampling by elk has been shown to damage vegetation in arid and semi-arid regions, while aiding in water infiltration and breaking up dead organic matter (Rupp 2000).

Studies indicate there has been recent land change at VC that coincide with changes in land-use. Forest encroachment into grassland areas in Valle Grande has occurred (Coop and Givnish 2007), and there are impacts on streams in VC due to sustained overgrazing by sheep and cattle during the period of private ownership (Parmenter 2009). The effects of heavy grazing have led to high temperature and increased turbidity in streams, leading to the designation of “impaired” by the New Mexico Department of Environmental Quality (Parmenter 2009). Impacts from historical logging persist, with higher fire danger due to dense tree canopies (Parmenter 2009), resulting in a loss of snow water equivalent in high canopy density areas (Veatch 2008). More recently, changes to forest structure brought about by the wildfires of 2011 and 2013 have added to the mosaic of disturbed landcover at VCNP.

2.5 LULCC

Remote sensing provides a way to consistently monitor biophysical characteristics and human-induced landscape change (Jensen 2007). Its synoptic perspective enables detection of regional scale changes in land cover through repeated collections over time. Changes in land cover are detected by changes in spectral response over time. A major advantage of remote sensing is that it is a cost-effective way to analyze land cover over large geographic areas (Lunetta et al. 2006).

The Landsat series of moderate resolution remote sensing satellites, in particular, has been shown to be an effective tool for deriving land cover at regional and continental scales (Xian, Homer, and Fry 2009) and measuring land cover changes (Akinyemi 2012). The Landsat program represents the longest continuously collected record of the earth's surface; extending from Landsat 1's launch in 1972 to the present (NASA). The recent launch of Landsat 8 on February 11, 2013 ensures Landsat's mission will continue for the foreseeable future.

3.0 Methodology

This study performed pre-classification change detection of three Landsat Thematic Mapper (TM) scenes and one Operational Land imager (OLI) scene to estimate the amount of landscape change between 1989-1999, 1999-2003, 2003-2013, and total change, 1989-2013. The time period includes 10 years of private ownership as the Baca Ranch (1989-1999), and ten years of management by VCT (2003-2013). The period of interim management by the USFS was approximated by the change period of 1999-2003. The USFS interim management actually took place from July 25, 2000- August 2, 2002 (VCT 2012), but there were no cloud-free images available for 2002. The inclusion of this interim period ensured that changes quantified for the periods of private and VCT management not include changes that took place outside of their respective management periods.

3.1 Study Area

VCNP is a 35,977 ha (88,900 acre) nature preserve located in the Jemez Mountain Volcanic Field (JMVF) commonly called the Jemez Mountains. The preserve is roughly five miles west of the city of Los Alamos and is bordered by Santa Fe National Forest, Bandelier National Monument, and Santa Clara Pueblo. The area administered by the

VCT is slightly smaller than the actual size of the geologic resurgent caldera. See Figure 1 for a map of Valles Caldera National Preserve.

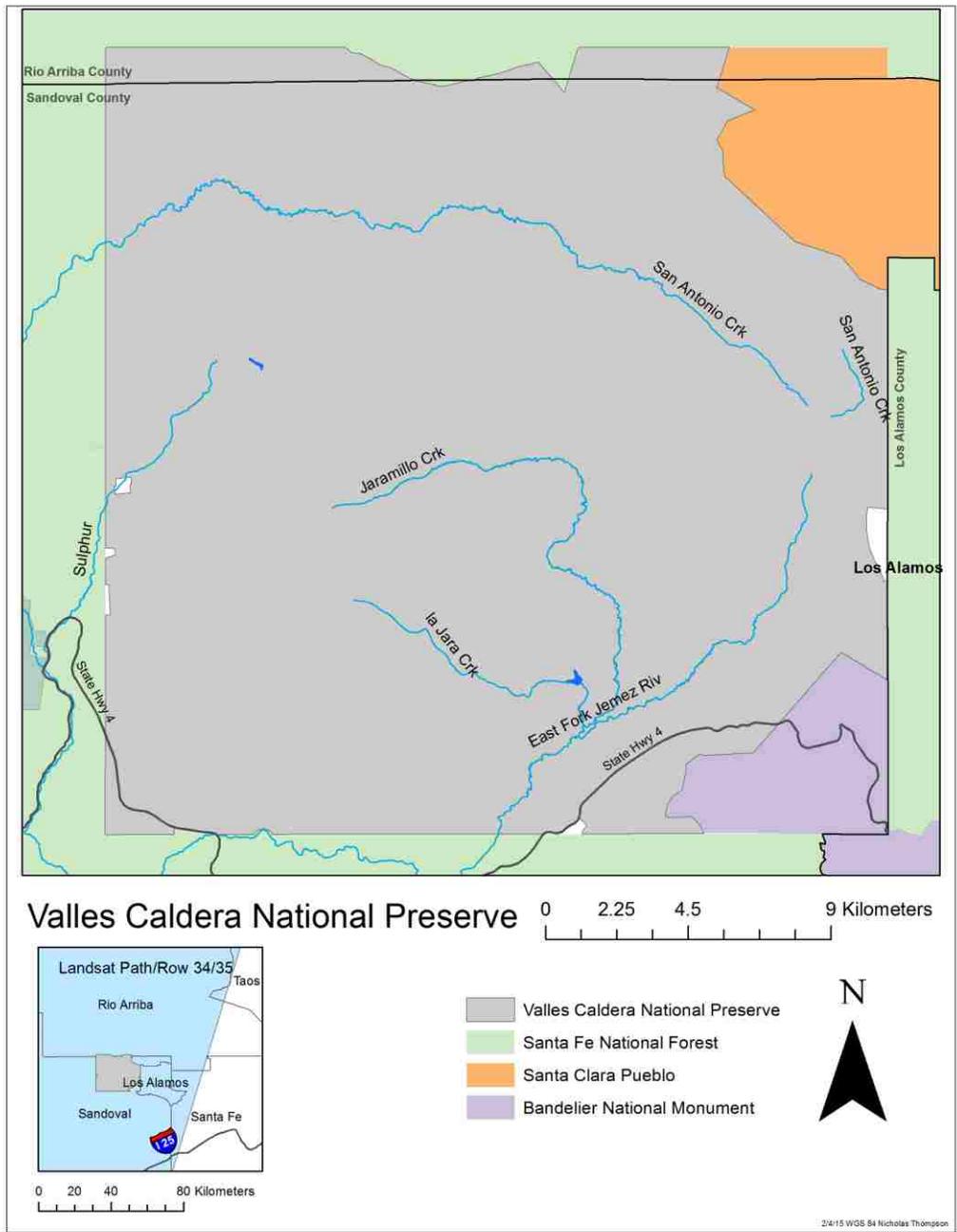


Figure 1: A map of Valles Caldera National Preserve. Blue shading in inset map shows Landsat 34/35 path row extent over study area.

3.2 Data

Data used for the analysis are summarized in Table 1. To identify changes that have occurred during the change periods within the present-day boundaries of VCNP, Landsat TM and OLI data from 1989,1999,2003, and 2013 were used to analyze changes during private management and VCT management, respectively. The Landsat platform provides a necessary spatial resolution of 30m with a temporal resolution of 16 days. Path 34 Row 35 and provides sufficient coverage of the study area. TM bands 1-5 and 7 and OLI bands 2-7 were used in the analysis. This band selection allows comparability between TM scenes and the OLI scene since the two sensors measure similar wavelengths at the same spatial resolution (30m) (Table 2).

Data Set	Data Format	Source
Landsat Image Data (1989, 1999, 2003, 2013)	30m raster	USGS Earth Explorer
MaxT NDVI	1 km raster	USGS
2000 Land Cover Map	36m raster	EDAC
Landownership Boundary	Vector-polygon	BLM
Township Boundaries	Vector-polygon	2010 TIGER Census Data
NM Counties	Vector- polygon	2010 TIGER Census Data
NM DOT Roads	Vector – polyline	RGIS
NAIP Imagery (2005, 2014)	1m raster CIR	RGIS
NAPP Imagery (1991)	1m raster CIR	USGS Earth Explorer
USGS Imagery	1m raster panchromatic	
USFS Aerial Imagery	1m hard copy true-color	On file at EDAC
Landsat path/row extent	Vector- polygon	USGS
Fire History	Vector- polygon	Santa Fe National Forest
Logging History	Vector - polygon	Belmat and Kupfer 2004

Table 1: Summary of datasets used in the analysis

Thematic Mapper (TM)		Operational Land Imager (OLI)	
Wavelength (μm)	Native band designation	Wavelength (μm)	Native band designation
0.45-0.52	Band 1	0.45-0.51	Band 2
0.52-0.60	Band 2	0.53-0.59	Band 3
0.63-0.69	Band 3	0.64-0.67	Band 4
0.76-0.90	Band 4	0.85-0.88	Band 5
1.55-1.75	Band 5	1.57-1.65	Band 6
2.08-2.35	Band 7	2.11-2.29	Band 7

Table 2: Comparison of TM and OLI bands

In order to minimize the detection of false changes due to environmental conditions, such as discrepancies in the timing of annual rainfall, Landsat image dates were determined by targeting the peak normalized different vegetation index (NDVI) recorded by the annual maximum NDVI (MAXT) dataset available for download from the United States Geological Survey (USGS). NDVI demonstrates relative vegetation vigor by ratioing the red and NIR reflectance and can effectively measure plant health due to the structure of vegetation with chlorophyll cells absorbing red wavelengths, and mesophyll cells scattering NIR wavelengths. The MAXT data measures when annual maximum NDVI occurred. NDVI measures “greenness”, or vigor, based on a -1 to 1 scale. The measure is closely associated with primary productivity and has been shown to be effective to measure changes in productivity in arid and semi-arid environments (Weiss et al. 2004). Pixel values in the MAXT layers typically range from 1-365 representing when maximum NDVI occurred during the year. The day of peak recorded NDVI values for the study

years (1989, 1999, 2003, 2013) were determined from the average value of a digitized 2x2 grassland polygon (Table 3) and Landsat scenes were selected as close as possible to those dates. Cloud contamination was often present given the correlation between seasonal rainfall and maximum NDVI so the next available cloud-free image date was selected following peak NDVI (See Table 3). All Landsat scenes were downloaded as GeoTiffs from the Earth Explorer data portal hosted by the US Geological Survey.

Year	Peak NDVI date	Landsat Image date	Discrepancy from average max NDVI (days)	Landsat sensor
1989	8/13	8/25	+12	TM
1999	8/13	9/27	+48	TM
2003	8/20	9/22	+32	TM
2013	9/24	10/3	+9	OLI

Table 3: MAXT derived Landsat scene dates

Identification of land cover and land cover change categories was aided by a land cover map of VNCP made by Muldavin et al (2006) at the Earth Data Analysis Center (EDAC). The map is based on a combination of mosaicked ortho-rectified aerial photos taken from June to September 2001 and two Landsat ETM⁺ scenes from November 4, 1999, and June 4, 2001 (Muldavin et al. 2006). ETM⁺ scenes were taken from different months, November 6, 1999 and June 4, 2001, to emphasize phenological differences between plant types. The June scene emphasized warm early season grasses and deciduous vegetation, while the November scene emphasized coniferous forest (Neville 2013).

Ancillary data was used to aid in interpretation of from-to change categories, including: high-resolution air photos, differenced NDVI for each time period, annual precipitation data, and logging and wildfire boundary GIS layers. High-resolution air photos helped identify beginning and ending states of cover changes. Differenced NDVI from the Landsat scenes identified relative changes to vegetation for each change period. PRISM annual precipitation data further contextualized changes in rangeland and wetland areas. The logging and wildfire GIS layers identified harvested areas during private ownership, whereas the wildfire layer identified location and year of wildfires throughout the study period. Logging history GIS coverages originated from Balmat and Kupfer (2004) who examined logging pre-VCNP using historic aerial photos, NM State Forestry records, and timbering reports. Balmat and Kupfer described the extent of four pre-VCNP eras of logging taking place 1935-1963; 1963-1972; 1980-1991, 1992-2000. The logging data aided in the evaluation of forest clusters as to the likelihood of logging having taken place within a change cluster.

GIS data from the Santa Fe National Forest indicated wildfire extents from 1970-2014, with the exception of prescribed burns of less than 10 acres. During the period nine fires took place within present-day boundaries of VCNP. The wildfire extents and the years of disturbances established if the forest was recovering from fire or degraded due to fire during the evaluated change periods.

PRISM climate data from the University of Oregon was used to interpret grassland and wetland changes. Annual precipitation is tracked by PRISM by compositing weather station data and interpolating into 4km rasters.

3.3 Pre-processing

Preprocessing of remotely sensed data prior to change detection consisted of geometric rectification through image-to-image registration. Geometric correction places pixels in their proper planimetric locations (Jenson 2005). Image-to-image registration was used to minimize co-registration related false detections when image differencing (Jenson et al. 1993). Correct spatial registration is paramount when comparing multi-temporal images for change detection since misregistration causes spurious change (Lu et al. 2004).

While all images were previously corrected to USGS Level 1 standards, the 2013 image was geometrically corrected and rectified to a planimetric 2011 Landsat mosaic to a root-mean-square Error (RMSE) of <1 pixel using the image to map approach (see Table 4). 2nd order polynomial warping and nearest neighbor resampling was used to preserve pixel values (Jenson 2005). The additional scenes from 1989, 1999, and 2003 were registered to the rectified 2013 scene to facilitate image-to-image comparison. Registration was performed to a root mean square error (RMSE) of ≤ 0.5 pixels (15 m).

All resampled scenes were subset to VCNP boundaries prior to differencing.

Year	Type of registration	RMSE (meters)	Number of Ground Control Points (GCP)
1989 registration to 2013	Image to image	13.70	20
1999 registration to 2013	Image to image	14.94	20
2003 registration to 2013	Image to image	13.27	20
2013 registration to 2011 mosaic	Map to image	9.81	20

Table 4: Summary of type of image registration and RMSE

3.4 Change Analysis

There are several approaches to detecting binary change/no change figures. One such approach is image differencing (Singh 1989; Song and Woodcock 2001). Image differencing uses scenes spatially registered to one another from two dates, subtracted pixel-by-pixel, to produce a differenced image of changed/and no-change pixels (Singh 1989; Song and Woodcock 2001).

According to Jenson (2005), image differencing change detection is:

$$A_{t_2} - A_{t_1} = \Delta A$$

eq. 1

where:

-  Change pixel value
-  Brightness or Digital Number recorded at date 1
-  Brightness or Digital Number recorded at date 2
-  line number location
-  column number location
-  a single band

The equation produces positive and negative values that represent areas of change while values close to zero represent areas where no change has occurred (Coppin and Bauer 1996; Singh 1989). When viewed in a histogram, the differenced image will display changed pixels on each of the tails and unchanged pixels near the mean (Jenson 2005).

In order to detect land cover changes during the period of study and facilitate identification of change categories, difference images for each period were clustered using ERDAS Imagine's K-means unsupervised classifier and were initially clustered into 64 classes. The categories were "cluster-busted" as needed to produce fewer categories with consistent spectral change between dates. The resulting differenced images were thresholded based on the cluster means, rather than individual pixels values.

Appropriate thresholding of the differenced image is critical to change detection and determines change/no-change pixels (Lu et al. 2005). There are two methods for

determining threshold placement, (1) user trial and error in manually selecting the threshold and (2) empirically determining the appropriate threshold by standard deviation (Lu et al. 2005). Most often, placement of the threshold is aided by the user's familiarity of the study area as well as ancillary data (Hays and Sader 2001).

Thresholding was set through interactive image viewing on a per cluster basis that evaluated mean change of band values for the initial 64 k-means derived clusters. 16 and 32 bin histograms were generated from the mean change results to identify change thresholds. Natural breaks identified through inspection of the histograms were used to identify potential change clusters and non-change clusters. Potential change clusters were evaluated and labeled as change or non-change through identification of breaks in histograms and interactive viewing Landsat scenes and the higher resolution airborne imagery to identify beginning and ending condition of the Landsat scenes. (See Table 1)

Change classes identifying specific transition types were identified based on an ensemble of evidence. Coarse cover categories of forest, rangeland and wetland were identified as either degraded or recovering from a given driver. Given the land-use history at Valles Caldera, cover categories included easily identifiable drivers of change, such as fire and logging. Grazing was not included as a driver in rangeland and wetland categories due to the challenge of distinguishing between degradation and recovery of rangelands as being due to phenologic variation or changing range practices. For example, during the 20th century ranching a Valles Caldera changed from sheep to cattle

ranching post-WWII, however, there continues to be a lasting impact on watershed health from past sheep ranching (Parmenter 2009). Grazing was included as a driver for barren land in the case there were identifiable changes.

The specific classes included: forest recovery from fire, forest degraded due to fire, forest recovery from logging, forest degraded from logging, rangeland recovery, rangeland degradation, wetland recovery, wetland degradation, barren created from fire, barren created from logging, barren created from grazing, undefined, undefined recovery, and undefined degradation. Areas categorized as undefined included persistent mixed clusters after being busted or when a transition state couldn't be clearly defined based on available evidence. Undefined recovery and undefined degradation were assigned based on NDVI changes that took place per undefined class that were considered identifiable.

3.5 Supporting Evidence of Change Clusters

To support labeling of clusters, several ancillary datasets were used. Change clusters were labeled based on overall evidence generated from the datasets and interactive viewing of false color composites.

Normalized Differenced Vegetation Indices (NDVI) were calculated for each image date. Mean NDVI per change class was extracted and differenced to demonstrate relative

changes to vegetation that took place between the image dates. The differenced mean NDVI per change classes resulted in a negative or positive value that indicated if change classes had resulted in a loss or improvement of vegetation vigor for each change period.

Annual precipitation data for 1989-2013 was averaged from three 4KM-sized pixels located in Valle Grande and Valle Toledo to characterize variation in annual precipitation. Graphs were produced for each change period as well as the total changes to average precipitation that occurred between 1989-2013. Understanding the precipitation during a given change period helped distinguish between land cover changes that can be definitively attributed to land management practices versus those that may be due to climatic factors. (See Figure 2 for PRISM graph)

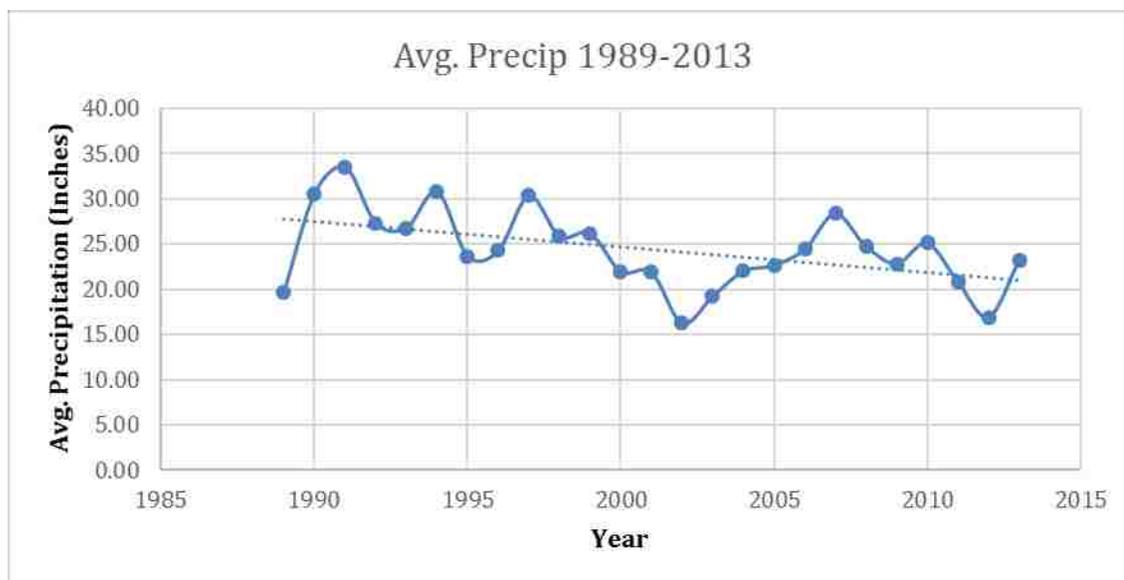


Figure 2: PRISM precipitation graph of grassland areas in Valles Caldera

The evidence from several sources (e.g., higher resolution imagery, differenced NDVI, PRISM precipitation data) aided in cluster labeling and evaluation of drivers of change. Through a combination of interactive viewing and presence/absence of known disturbances such as wildfire and logging, management-related drivers of change could be established and clusters labeled based on multiple lines of evidence.

4.0 Results

Results indicate large-scale land cover shifts at Valles Caldera during each period of ownership. Under private ownership, the Valles Caldera experienced some rangeland recovery, wetland recovery, and forest recovery from logging. Under VCT management, wetland and rangeland improvement occurred at a higher rate, but the single largest cover change is unrelated to the specific land management approach at the time, but instead forest degradation due to fire, which is likely a result of historical fire suppression and climatic factors.

Results of the cover change analysis in both total area (in km²) and the rate of change (in km²/year) are shown in Table 5. The rate of change was calculated in order to have comparability between change periods, as the USFS interim management period is only 4 years compared to the 10 year periods of private and VCT management. Figures 3, 4, 5, and 6 show the geographic distribution of the changes. Area changed (in km²) and rates of change (in km²/year) are depicted in Figure 7 and 8, respectively.

Total km ² of Change	1989-1999	1999-2003	2003-2013	1989-2013
Forest Recovery From Fire	0	0	0	0
Forest Degraded From Fire	0	0	81.9369	75.5109
Forest Recovery From Logging	7.0605	1.5804	0	1.359
Forest Degraded From Logging	0	0	0.5472	0
Rangeland Recovery	13.4937	0	41.0823	49.0455
Rangeland Degradation	0	35.4546	0	0
Wetland Recovery	5.5431	0	16.8363	31.6053
Wetland Degradation	0	6.8634	0	0
Barren	0.27	0	0.2169	0.4068
Barren Created From Fire	0	0	0	0.1791
Barren Created From Logging	0	0	0	0
Barren Created From Grazing	0	0	0	0
Undefined	0	0	0.7299	0.2286
Undefined Recovery	4.7385	0	9.4257	14.6925
Undefined Degradation	0	11.2986	0	0
Rates of Change (km ²)				
	1989-1999	1999-2003	2003-2013	1989-2013
Forest Recovery From Fire	0.00	0.00	0.00	0.00
Forest Degraded From fire	0.00	0.00	8.19	7.55
Forest Recovery From Logging	0.71	0.40	0.00	0.14
Forest Degraded From Logging	0.00	0.00	0.05	0.00
Rangeland Recovery	1.35	0.00	4.11	4.90
Rangeland Degradation	0.00	8.86	0.00	0.00
Wetland Recovery	0.55	0.00	1.68	3.16
Wetland Degradation	0.00	1.72	0.00	0.00
Barren	0.03	0.00	0.02	0.04
Barren Created From Fire	0.00	0.00	0.00	0.02
Barren Created From Logging	0.00	0.00	0.00	0.00
Barren Created From Grazing	0.00	0.00	0.00	0.00
Undefined	0.00	0.00	0.07	0.02
Undefined Recovery	0.47	0.00	0.94	1.47
Undefined Degradation	0.00	2.82	0.00	0.00

Table 5: Results

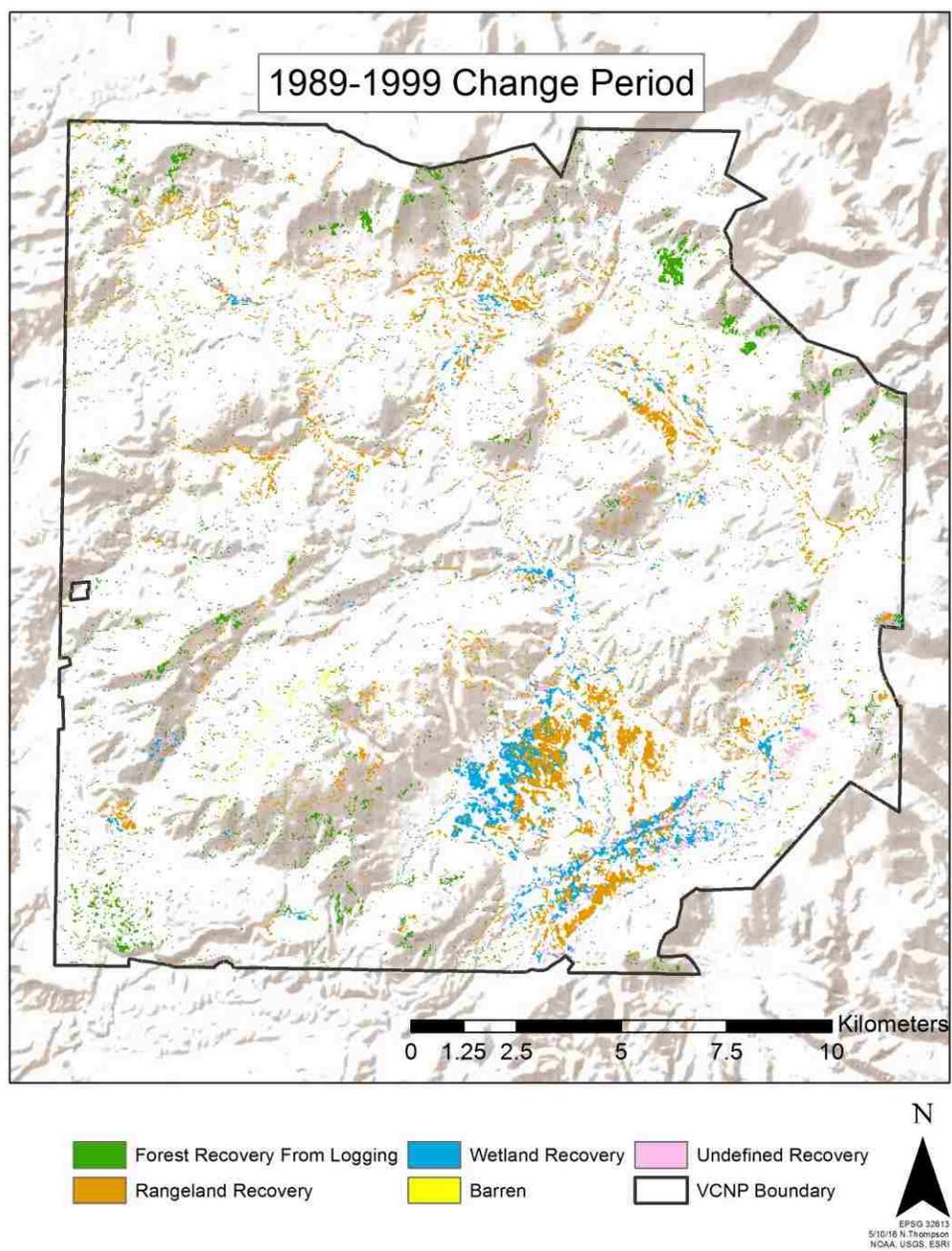


Figure 3: Change map from 1989-1999

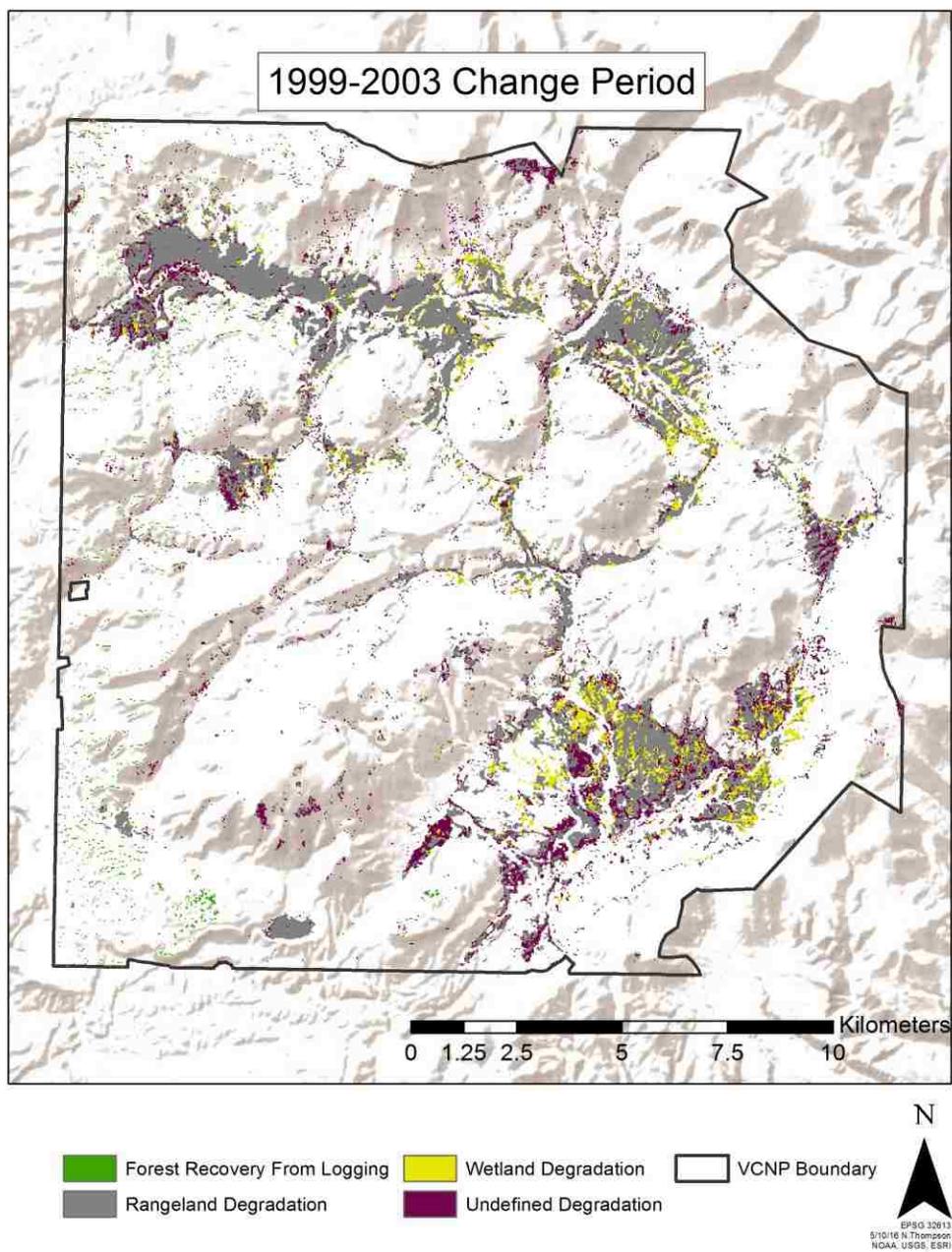


Figure 4: Change map from 1999-2003

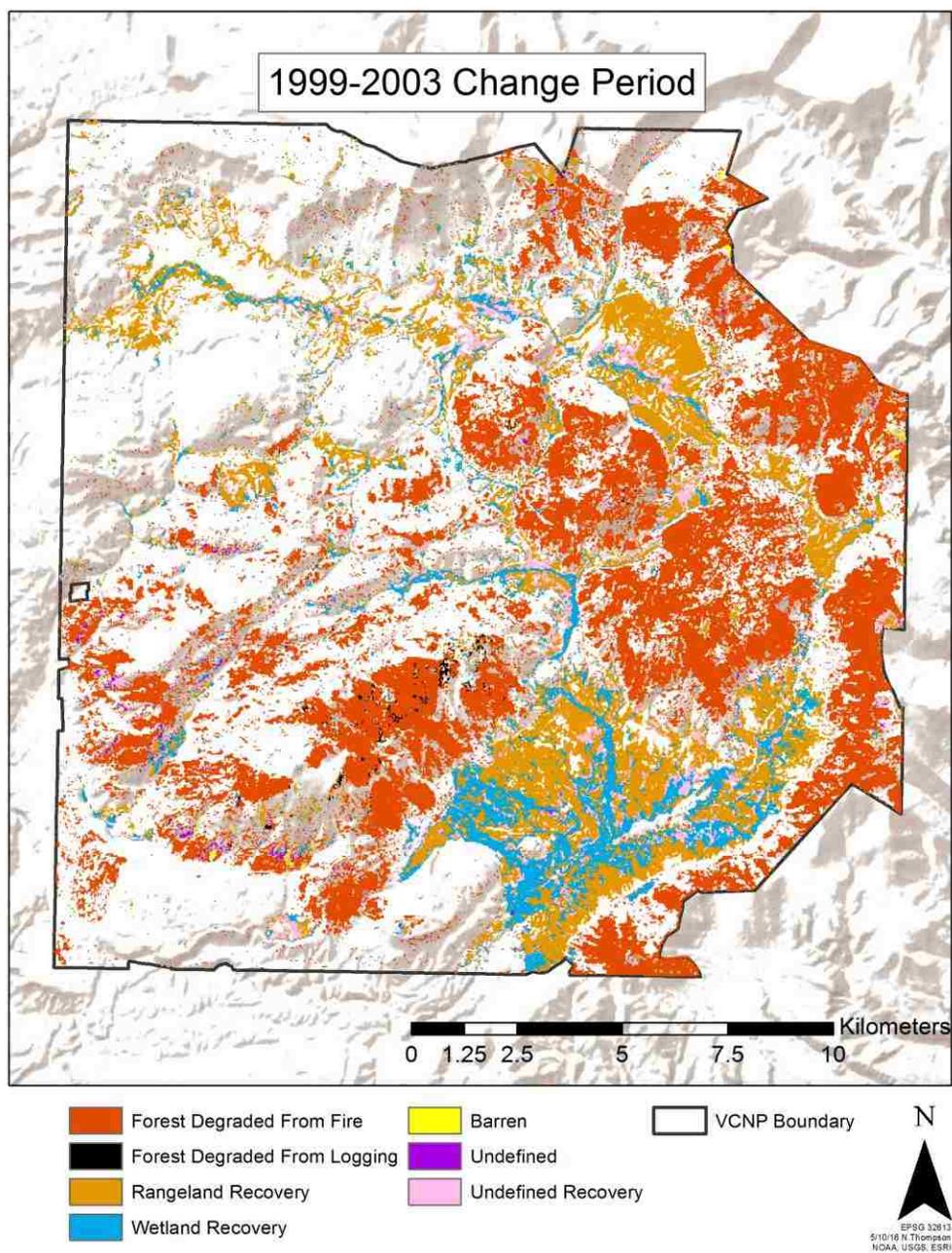


Figure 5: Change map from 2003-2013

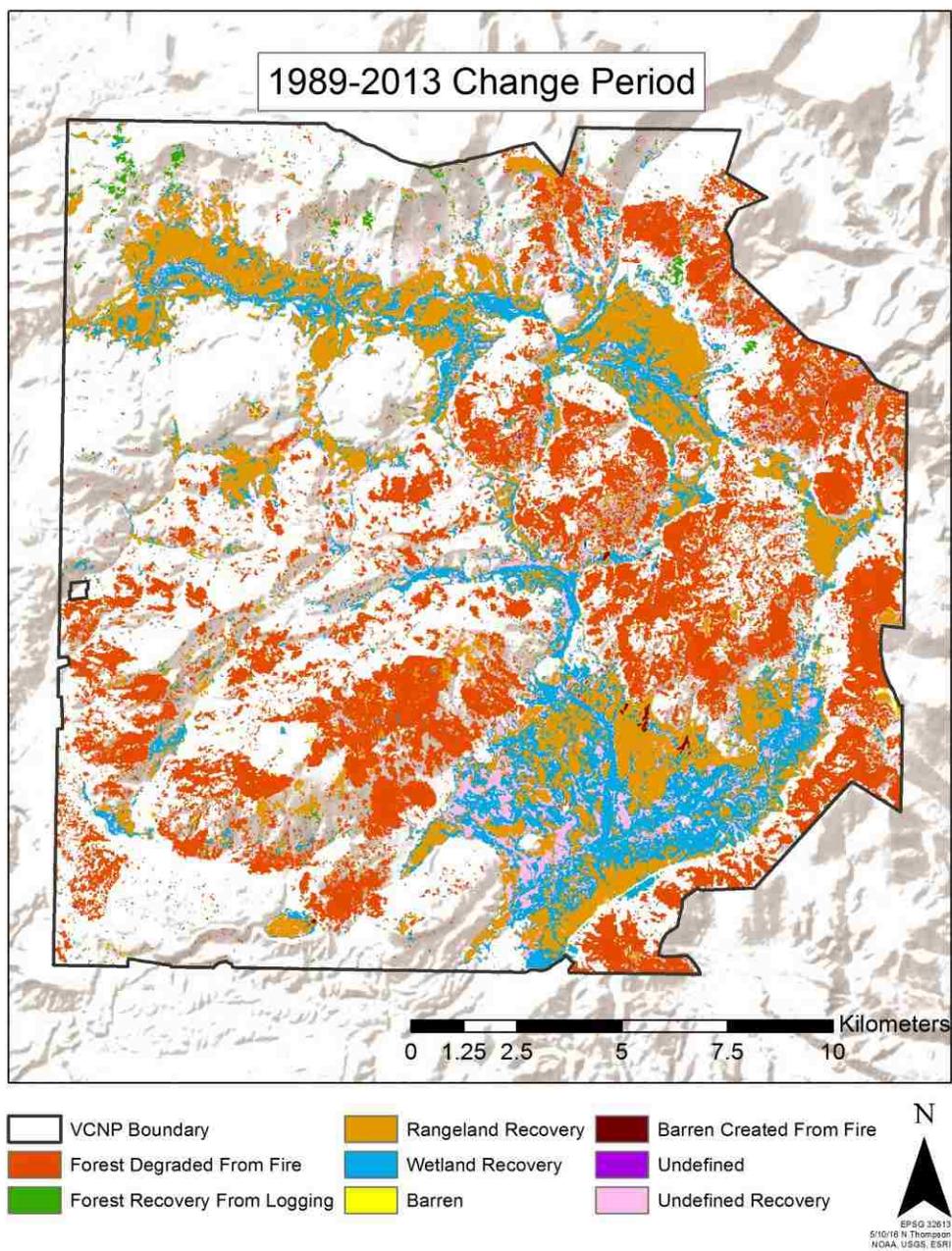


Figure 6: Change map from 1989-2013

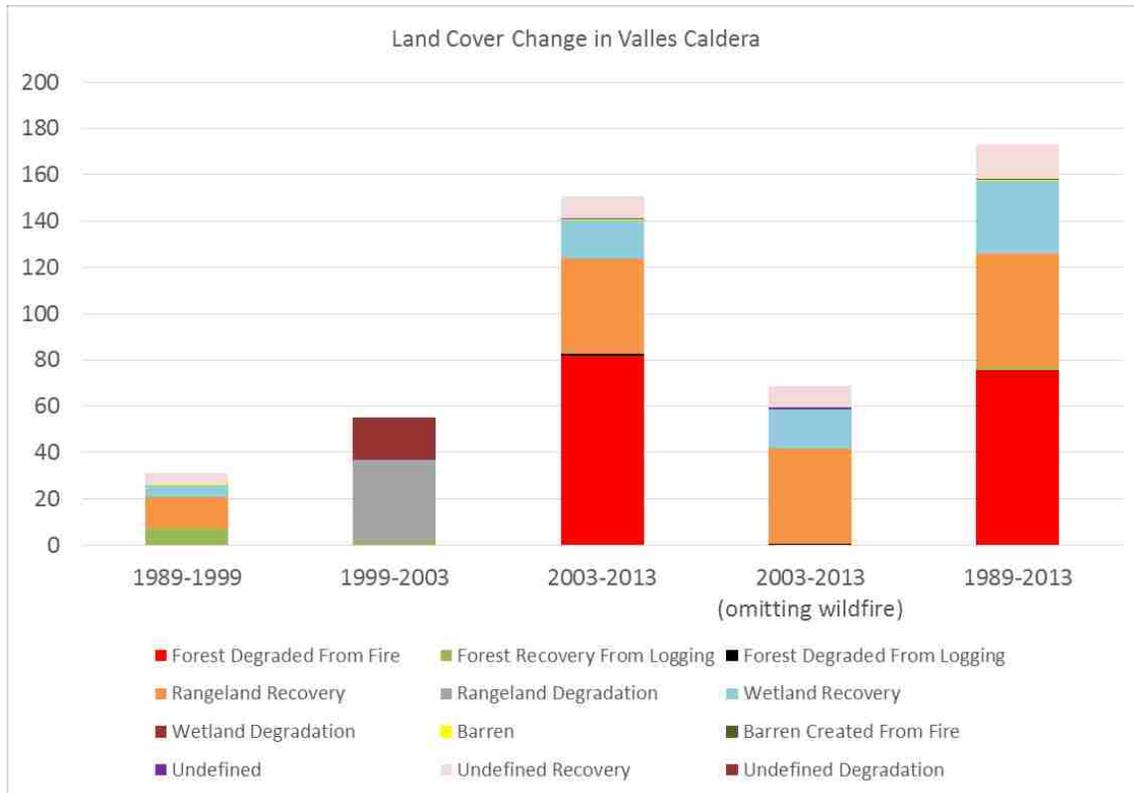


Figure 7: Graph of total land cover change that took place during the study.

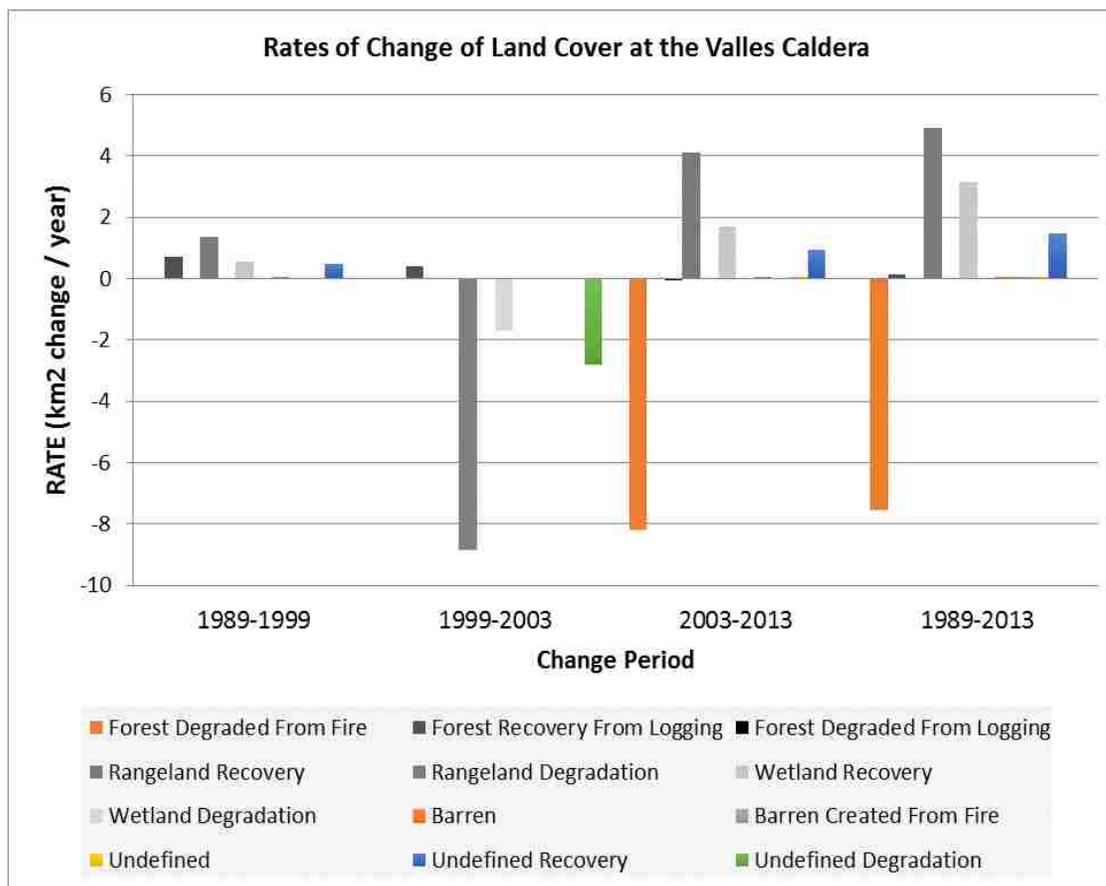


Figure 8: Graph of rates of land cover change that took place during the study. Degraded categories are scaled as negative values.

The 1989-1999 period, as shown in Figure 8, experienced changes related to forest recovering from logging, rangeland recovery, and wetland recovery. Within the area of the present-day preserve, forest recovery from past logging occurred at a rate of .71 km² per year. Rangeland recovery occurred at a rate of 1.35 km² per year and wetland recovery occurred at a rate of .55 km² per year.

The 1999-2003 change period (i.e., USFS interim management) experienced forest recovery from logging, rangeland degradation, and wetland degradation (Figure 8).

Forest Recovery in previously logged areas accounted for .40 km² of change per year. Rangeland and wetland areas degraded at a rate of 8.86 km² per year and 1.72 km² per year, respectively.

The 2003-2013 change period experienced forest degradation due to wildfire, forest degradation due to logging, rangeland recovery, and wetland recovery. Forest degradation due to wildfire occurred at a rate 8.19 km² per year (Figure 8). Rates of change for 2003-2013 (when wildfire is omitted from the period) is shown in Figure 8. Much of wildfire degradation can be attributed to historical land management practices, not present land management practices. Rangeland recovery and wetland recovery occurred at a rate of 4.11 km² per year and 1.68 km² per year, respectively. Forest degradation due to logging occurred at a rate of .05 km² per year.

The overall study period, 1989-2013, includes time periods of private and VCT management as well as interim USFS management. The overall study period experienced forest degradation due to fire at a rate of 7.55 km² per year and forest areas recovering from logging at a rate of .14 km² per year. Additionally, rangeland and wetland recovery occurred at a rate of 4.90 km² per year and 3.16 km² per year, respectively.

5.0 Discussion

The results show rangeland and wetland recovery took place during both private and VCT management. However, the period under VCT management shows a rate of rangeland and wetland recovery three times as high as the period under private management. Some of the rangeland, wetland, and forest recovery during the 1989-1999 change period may be attributable to the increase in annual precipitation between 1989 and 1999 (26.18 in). The increased rangeland and wetland health between 2003 and 2013 cannot be attributed to increased precipitation, as 2012 was a year of notable drought (See Figure 2), indicating that rangeland and wetland management by VCT may have played a role in the improvement of the categories.

Undefined change was persistent during all change periods with the majority occurring in wetland/grassland areas that couldn't be clearly identified following cluster busting (See Figures 3, 4, and 5). Though the overall period of 1989-2013 produced the largest total area of undefined change, the interim period of USFS management, 1999-2003, had the highest rate of change (See Table 5). Variability in the undefined category was likely due to a combination of factors including image dates that didn't allow for discrimination of wetland and rangeland areas based on the three dominant land cover categories found in Muldavin et al's (2006) land cover categories (See Figure 9). Further examination of the Undefined change categories by mean-differenced NDVI revealed

they behaved similarly to the rangeland and wetland recovery and degradation change categories present during each change period (Table 6). Upon further examination, undefined recovery accounted for the largest category of undefined change, accounting for 4.73 km² of change in 1989-1999, and 9.43 and 14.69km² of change during 2003-2013 and the total 1989-2013 periods, respectively.

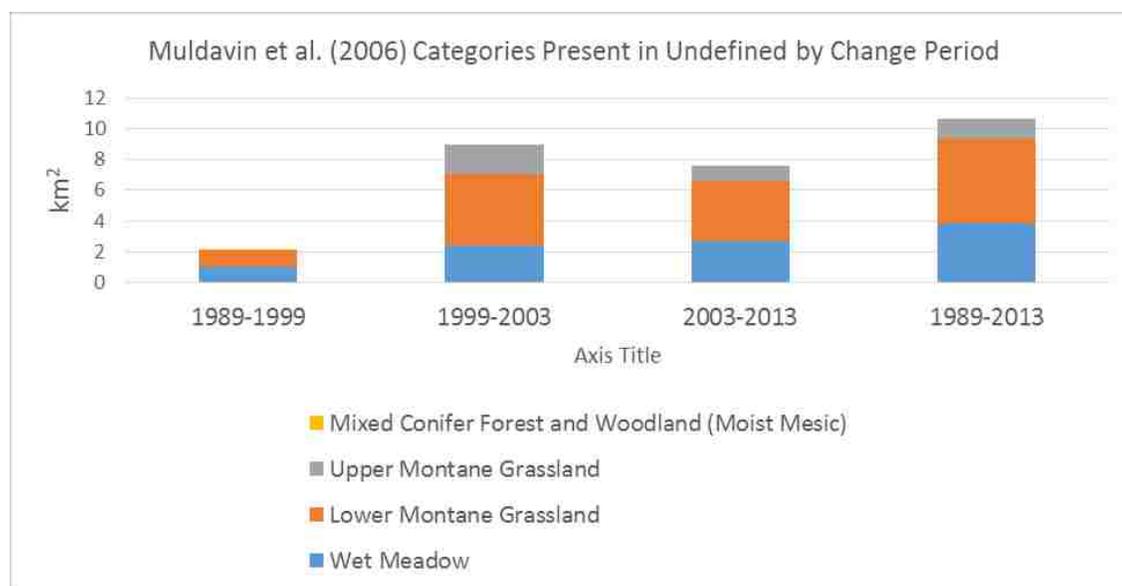


Figure 9: Graph comparing Muldavain et al.'s (2006) land cover categories to the Undefined Change Category.

Mean Δ NDVI	1989-1999	1999-2003	2003-2013	1989-2013
Undefined	0	0	.01	.03
Undefined Recovery	.06	0	.19	.16
Undefined Degradation	0	-.058	0	0

Table 6: Undefined Change Category Differenced Mean NDVI.

The data from the 1999-2003 change period, approximately the time of the USFS interim management, indicate both rangeland and wetland degradation that may have impacted marketed improvements in the categories that took place during the next period. Change rates from improving rangeland and wetland conditions from 2003-2013 period, may be due to a recovery from highly stressed wetland and rangeland vegetation and not just attributable to VCT adaptive management practices. Variable phenology may have also affected the comparison of grasses and wetlands since there was a large discrepancy in image dates from peak greenness for both 1999 and 2003 (See Table 3).

The increased rate of wetland and rangeland improvement under VCT management indicates that adaptive management strategies were beneficial for these cover types. Wetland and Rangeland improvements occurred throughout the preserve, not just in areas excluded from grazing. Comparing the 2003-2013 and 1989-2013 rates of change indicates a link between VCT-adaptive management and recovery for the two categories. Comparing the two time periods demonstrates a higher rate of change taking place in rangeland and wetland areas compared to 1989-2013. The higher rates of change during VCT management suggest that adaptive management produced higher rates of rangeland and wetland recovery during a downward trend in annual precipitation that took place during 1989-2013 (See Figure 2).

Specific management actions enacted by VCT that may have contributed to rangeland and wetland recovery were tied to the grazing program. Under VCT, 60% of biomass was marked for ecosystem services (Haarman 2012). Additionally, stocking numbers were far lower under VCT than private ownership. Efforts were made to reduce impacts through grazing, with a reduction of 80-90% of cattle kept on the preserve resulting in wetland recovery (Parmenter, Steffen and Allen 2007). VCT also made efforts both to experiment with existing range, such as burning a portion of rangeland in 2006, while also limiting cattle access to wetland areas by fencing off thousands of acres (Valles Caldera Trust 2012). Additionally, some changes to ranch infrastructure likely contributed to lessening in cattle-grazing related impacts, such as the use of drinkers for livestock watering (Valles Caldera Trust 2012).

VCT-management contributing to greater rates of wetland and rangeland recovery is suggested when comparing PRISM data to expected elk wintering behavior. Elk overwintering is tied to snow depth and may be in the largest determining factor in seasonal elk migration (Wolf 2003). The expectation would be that more precipitation in the form of snow would lead to greater herd migration to lower elevations. However, comparing average rates of the PRISM data indicates less annual precipitation during the period of VCT management vs. private ownership (See Figure 2). This would likely contribute to larger numbers of elk overwintering in Valles Caldera, which would likely

be met with rangeland and wetland degradation. Large portions of elk overwintering at Valles Caldera coupled with drought was a cited reason for cancellation of the 2006 grazing season (Valles Caldera Trust 2006). More research on snow precipitation is needed to make a definitive conclusion since the PRISM data used in this study was based on annual measurements of precipitation that do not distinguish between snow and other types of precipitation.

It is more difficult to draw conclusions about adaptive forest management because forest changes, both recovery and degradation, are slower processes. Additionally, several wildfire events took place during the study during the 2003-2013 change period. Both change periods of 2003-2013 and the overall period of 1989-2013 show roughly the same amount of change in Forest Degraded due to Wildfire. However, much of forest degradation due to fire can be attributed to historical management of the forest, instead of present forest management. This is based on a number of past land uses, such as past logging, grazing, and alterations in fire return interval playing a role in increasing fire hazard (Allen 2002a). Forest Recovery from logging, present in 1989-1999 was undetectable during the VCT-managed period, which may have been due to reaching a recovered or nearly recovered state. Belmat and Kupfer's 2004 stated that less overall logging has taken place from 1992-2000. Additionally, some areas of the preserve that were logged during 1992-2000 were then subject to prescribed burning by

the VCT (VCT 2012). These factors likely contributed to the absent rate of recovery from logging during the VCT-managed period of 2003-2013.

6.0 Conclusion

This study offers a brief look into how land-use policies play a role in determining observable biophysical characteristics. Valles Caldera has undergone significant shifts as humans have interacted with the environment for thousands of years. The *valle* has provided resources to humans for many years and serves as a place of cultural significance. When shifts towards more intensive land-use patterns and competing goals of forest management emerged in the early 20th century, significant alterations occurred in fire-return intervals, affecting forests and rangelands alike. The federal government purchased the property in 2000, which marked a significant change in ownership structure and management goals.

This study aims to evaluate the effect of the change in ownership structure and management goals on land cover change at the Valles Caldera. To do this, data was evaluated to show rates of change in land cover for the final 10-year period of private ownership, from 1989-1999, and the first 10-year period of management under the Valles Caldera Trust (VCT), from 2003-2013. The data shows variances in the rates of wetland and rangeland recovery between each management period. The magnitude of wetland and rangeland recovery during the VCT managed change period was three times larger than the magnitude of wetland and rangeland recovery during the privately

managed period, suggesting that VCT's adaptive management strategies were beneficial to these cover types.

Unlike wetland and rangeland recovery, forest regrowth is a longer process and, both vegetation recovery and wildfire return intervals are closely related to past management practices. Therefore, it is more difficult to associate forest changes with the specific periods of management. Past grazing, logging, and a longer fire return interval likely contributed to the two large wildfires during VCT management. Likewise, recovery from logging occurred in the period immediately preceding extensive logging. This change category had the highest rate of change in 1989-1999 followed by tapering during USFS management. Forest degradation from logging was only detectable during VCT management, but may have been due to fire-related activities. Additionally, barren land is difficult to associate with management activities since it may have occurred from a variety of circumstances.

Resource management is subject to competing goals over time. This study offers a short look into how land-use and policies can play a role in determining observable biophysical characteristics.

7.0 References

- Allen, Craig D. 2015. "From the Jemez Mountains to Planet Earth: Patterns, Trends, and Drivers of Increasing Forest Die-Offs and Wildfires with Emerging Hotter Droughts in the Anthropocene", 2015. Lecture.
- Allen, Craig D. 2001. "Fire and vegetation history of the Jemez Mountains." *Water, Watersheds, and Land-use In New Mexico: Impacts of Population Growth on Natural Resources, Santa Fe Region 2001*:29-33.
- Allen, Craig D, Julio L Betancourt, and Thomas W Swetnam. 1998. "Landscape changes in the southwestern United States: techniques, long-term data sets, and trends." *Perspectives on the Land-Use History of North America: A Context for Understanding Our Changing Environment. Fort Collins (CO): US Geological Survey*:71-84.
- Allen, Craig D, Melissa Savage, Donald A Falk, Kieran F Suckling, Thomas W Swetnam, Todd Schulke, Peter B Stacey, Penelope Morgan, Martos Hoffman, and Jon T Klingel. 2002a. "Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective." *Ecological applications* 12 (5):1418-1433.
- Allen, Craig R, and Lance H Gunderson. 2011. "Pathology and failure in the design and implementation of adaptive management." *Journal of Environmental Management* 92 (5):1379-1384.
- Anderson, J.R. (1976). A land-use and land cover classification system for use with remote sensor data. US Government Printing Office
- Anschuetz, K., & Raish, C. (2010). Public views and attitudes concerning fire and fuels reduction strategies in the Valles Caldera National Preserve (VCNP) New Mexico
- Anschuetz, Kurt F. 2007. "A Sketch of the Cultural-Historical Environment—Part 1: The Pre-Columbian Past." *Valles Caldera National Preserve Land-use History*:11.
- Anschuetz, Kurt F, and Thomas Merlan. 2007. "More than a scenic mountain landscape: Valles Caldera National Preserve land-use history."
- Balmat, Jeff, and John Kupfer. "Assessment of timber resources and logging history of the Valles Caldera National Preserve." *University of Arizona Technical Report VCT04011 for Valles Caldera Trust, Tucson, Arizona, USA*(2004).
- Benson, M. H. (2015). "Shifting Public Land Paradigms: Lessons from the Valles Caldera National Preserve." *Virginia Environmental Law Journal, Forthcoming*: 2015-2021.
- Bogan, MA, CD Allen, EH Muldavin, SP Platania, JN Stuart, GH Farley, P Mehlhop, and Jayne Belnap. 1998. "Southwest." *Status and trends of the nation's biological resources*:543.

- Coop, Jonathan D, and Thomas J Givnish. 2007. "Spatial and temporal patterns of recent forest encroachment in montane grasslands of the Valles Caldera, New Mexico, USA." *Journal of Biogeography* 34 (5):914-927.
- Coop, Jonathan D, and Thomas J Givnish. 2008. "Constraints on tree seedling establishment in montane grasslands of the Valles Caldera, New Mexico." *Ecology* 89 (4):1101-1111.
- Coppin, P.R., & Bauer, M.E. (1996). Digital change detection in forest ecosystems with remote sensing imagery. *Remote sensing reviews*, 13, 207-234
- de Koning, Gerardus HJ, Peter H Verburg, A Veldkamp, and LO Fresco. 1999. "Multi-scale modelling of land-use change dynamics in Ecuador." *Agricultural systems* 61 (2):77-93.
- Dewar, Jacqueline Joy. 2011. "Fire history of montane grasslands and ecotones of the Valles Caldera, New Mexico, USA." THE UNIVERSITY OF ARIZONA.
- "Earth Observatory," NASA, Accessed March 6, 2016, http://earthobservatory.nasa.gov/Features/MeasuringVegetation/measuring_vegetation_2.php
- "Examples of Cable Yarding Systems (From the Washington State Safety Standards for Logging Operations)," OSHA, Accessed March 8, 2016, https://www.osha.gov/SLTC/etools/logging/manual/yarding/example_systems.html
- Elson, Jerry W. 1992. "Tri cultures of New Mexico." *Rangelands*:261-264.
- Falk, Donald A, Craig Allen, Robert Parmenter, Thomas Swetnam, and Clifford Dils. 2011. "Fire Regimes of Montane Grasslands of the Valles Caldera National Preserve, New Mexico."
- Fawcett, P.J., Werne, J.P., Anderson, R.S., Heikoop, J.M., Brown, E.T., Berke, M.A., Smith, S.J., Goff, F., Donohoo-Hurley, L., & Cisneros-Dozal, L.M. (2011). Extended megadroughts in the southwestern United States during Pleistocene interglacials. *Nature*, 470, 518-521
- French, A., Schmutge, T., Ritchie, J., Hsu, A., Jacob, F., & Ogawa, K. (2008). Detecting land cover change at the Jornada Experimental Range, New Mexico with ASTER emissivities. *Remote Sensing of Environment*, 112, 1730-1748
- Gess, Peter Larry. 2006. "A Grand Experiment in Public Lands Management: Responsiveness in the Valles Caldera National Preserve." University of Georgia.
- "Global Land Cover Facility," University of Maryland, Accessed December 4, 2014, <http://glcf.umd.edu/services/landcoverchange/>

- Goff, Fraser. 2002. "Geothermal potential of Valles Caldera, New Mexico." *GEO-HEAT CENTER Quarterly Bulletin*:7.
- Haarman, Tim. 2012. "2012 VCNP Livestock Grazing Report." *Valles Caldera Trust* (33).
- Heiken, Grant, Fraser Goff, Jamie N Gardner, WS Baldrige, JB Hulen, Dennis L Nielson, and David Vaniman. 1990. "The Valles/Toledo Caldera Complex, Jemez Volcanic Field, New Mexico." *Annual Review of Earth and Planetary Sciences* 18:27.
- Holling, Crawford S. 1978. "Adaptive environmental assessment and management." *Adaptive environmental assessment and management*.
- "Land-use and Cover Change," *International Geosphere-Biosphere Programme*, Date unknown, Accessed November 16, 2014, <http://www.igbp.net/researchprojects/pastprojects/landuseandcoverchange.4.1b8ae20512db692f2a680009062.html>
- Jensen, J., Cowen, D., Althausen, J., NARUMALANI, S., & WEATHERBEE, O. (1993). An evaluation of the CoastWatch change detection protocol in South Carolina. *Photogrammetric Engineering and Remote Sensing*, 59, 1039-1044
- Jenson, John R (2007). *Remote Sensing of the Environment*. In: Upper Saddle River, NJ: Pearson Prentice Hall
- Jensen, J.R. (2005). *Introductory digital image processing 3rd edition*. In: Upper Saddle River: Prentice Hall
- Jensen, J.R., Ramsey, E., Mackey Jr, H., Christensen, E., & Sharitz, R. (1987). Inland wetland change detection using aircraft MSS data. *Photogrammetric engineering and remote sensing (USA)*
- Kelly, Maggi, Shasta Ferranto, Shufei Lei, Ken-ichi Ueda, and Lynn Huntsinger. 2012. "Expanding the table: the web as a tool for participatory adaptive management in California forests." *Journal of environmental management* 109:1-11.
- Lambin, Eric F, Bi L Turner, Helmut J Geist, Samuel B Agbola, Arild Angelsen, John W Bruce, Oliver T Coomes, Rodolfo Dirzo, Günther Fischer, and Carl Folke. 2001. "The causes of land-use and land-cover change: moving beyond the myths." *Global environmental change* 11 (4):261-269.
- "Landsat Science," *NASA*, Date unknown, Accessed November 10, 2014. http://landsat.gsfc.nasa.gov/?page_id=2
- Lepers, Erika, Eric F Lambin, Anthony C Janetos, RUTH DeFRIES, Frédéric Achard, Navin

- Ramankutty, and Robert J Scholes. 2005. "A synthesis of information on rapid land-cover change for the period 1981–2000." *BioScience* 55 (2):115-124.
- Lunetta, Ross S, Joseph F Knight, Jayantha Ediriwickrema, John G Lyon, and L Dorsey Worthy. 2006. "Land-cover change detection using multi-temporal MODIS NDVI data." *Remote sensing of environment* 105 (2):142-154.
- Lu, D., Mausel, P., Brondizio, E., & Moran, E. (2004a). Change detection techniques. *International journal of remote sensing*, 25, 2365-2401
- Merlan, Thomas. 2007. "A Sketch of the Cultural-Historical Environment—Part 2: Spanish Entradas to the Present." *Valles Caldera National Preserve Land-use History*:25.
- Merlan, Thomas, Anschuetz, Kurt F. 2007a. "Ranching History." *Valles Caldera National Preserve Land-use History*:107
- Merlan, Thomas, Anschuetz, Kurt F. 2007a. "History of the Baca Location No. 1." *Valles Caldera National Preserve Land-use History*:107
- Muldavin, Esteban, Nevile, Paul, Jackson, Charlie, Neville, Teri. (2006). A Vegetation Map of Valles Caldera National Preserve, New Mexico. Report to Valles Caldera Trust
- Neville, Paul, e-mail message to author, September 15, 2014.
- Parmenter, R., Steffen, A., & Craig, D. (2007). An overview of the Valles Cadera National Preserve: the natural and cultural resources. *New Mexico Geological Society Guidebook*, 58, 147-154
- Parmenter, Robert R. 2009. "Applying hydrology to land management on the Valles Caldera National Preserve."
- Parmenter, Robert R, email-message to author, March 29, 2016.
- Paskus, Laura. Trouble on the Valles Caldera. *High Country News*, November 28, 2005. <http://www.hcn.org/blogs/issues/311/15943>
- Rudel, Thomas K, Oliver T Coomes, Emilio Moran, Frederic Achard, Arild Angelsen, Jianchu Xu, and Eric Lambin. 2005. "Forest transitions: towards a global understanding of land-use change." *Global Environmental Change* 15 (1):23-31.
- Rupp, Susan P. 2000. "Effects of grazing and trampling by Rocky Mountain elk (*Cervus elaphus nelsoni*) on the vegetative community of Bandelier National Monument, New Mexico." Texas Tech University.

- Scanlon, Bridget R, Robert C Reedy, David A Stonestrom, David E Prudic, and Kevin F Dennehy. 2005. "Impact of land-use and land cover change on groundwater recharge and quality in the southwestern US." *Global Change Biology* 11 (10):1577-1593.
- Singh, A. (1989). Review article digital change detection techniques using remotely-sensed data. *International journal of remote sensing*, 10, 989-1003
- Song, C., Woodcock, C.E., Seto, K.C., Lenney, M.P., & Macomber, S.A. (2001). Classification and change detection using Landsat TM data: when and how to correct atmospheric effects? *Remote sensing of Environment*, 75, 230-244
- Tillery, Anne C, Michael J Darr, Susan H Cannon, and John A Michael. 2011. "Postwildfire preliminary debris flow hazard assessment for the area burned by the 2011 Las Conchas Fire in north-central New Mexico." *US Geological Survey Open-File Report* 1308 (11).
- Touchan, Ramzi, Craig D Allen, and Thomas W Swetnam. 1996. "Fire history and climatic patterns in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico." *UNITED STATES DEPARTMENT OF AGRICULTURE FOREST SERVICE GENERAL TECHNICAL REPORT RM:33-46*.
- Valles Caldera Preservation Act. 2000, Public Law 106-248.
- Valles Caldera Trust a. *2012 Report to Congress Fiscal Year 2012*.
<<http://www.vallescaldera.gov/about/Trust/docs/AnnualReportCongress2012.pdf>>
- Valles Caldera Trust. *2006 Report to Congress Fiscal Year 2006*.
<<https://www.nps.gov/vall/learn/management/upload/VALLAnnualReportCongress2006.pdf>>
- Valles Caldera Trust b. *Soils: Existing Condition Report*
<http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5383833.pdf>
- "Valles Caldera: Trust Has Made Some Progress, but Needs to Do More to Meet Statutory Goals," GAO November 16, 2005
<<https://www.gpo.gov/fdsys/pkg/GAOREPORTS-GAO-06-98/html/GAOREPORTS-GAO-06-98.htm>>
- Veatch, William C. *Quantifying the Effects of Forest Canopy Cover on Net Snow Accumulation at a Continental, Mid-latitude Site, Valles Caldera National Preserve, New Mexico, USA*. ProQuest, 2008.
- Veldkamp, Antonie, and Eric F Lambin. 2001. "Predicting land-use change." *Agriculture, ecosystems & environment* 85 (1):1-6.

Wolf, E. D. (2003). Modeling elk distribution in Bandelier National Monument, New Mexico, Texas Tech University.

Williams, A.P., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., & Grissino-Mayer, H.D. (2013). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, 3, 292-297

Williams, A Park, Craig D Allen, Constance I Millar, Thomas W Swetnam, Joel Michaelson, Christopher J Still, and Steven W Leavitt. 2010. "Forest responses to increasing aridity and warmth in the southwestern United States." *Proceedings of the National Academy of Sciences* 107 (50):21289-21294.

Xian, George, Collin Homer, and Joyce Fry. 2009. "Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods." *Remote Sensing of Environment* 113 (6):1133-1147.