UNIVERSITY OF CALGARY

Changes in Bighorn Sheep Habitat of the Sierra Nevada

by

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A DOCUMENT
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF GIS

DEPARTMENT OF GEOGRAPHY

CALGARY, ALBERTA

SEPTEMBER, 2010

Abstract

The bighorn sheep population of the Sierra Nevada in California has been reduced in the last century to several small discrete herd units, and may be suffering negative effects from landscape change since early human settlement. A change-detection study was performed in the bighorn sheep herd units with substantial low elevation forest using a manual photointerpretation method on historical aerial imagery from the 1920s and 1940s. Basic terrain variables, such as slope, aspect, elevation, as well as latitude and tree cover from 2005 were explored in linear mixed model regression as predictors of vegetation change. Change was less than <3% on average for each herd unit, although there was substantial variation observed. The Mt. Gibbs and Mt. Williamson herd units were associated with low elevation change occurring on the south and south-east fringes, while low slopes and high tree cover areas were associated with change in the Mt. Warren herd unit. Mt. Langley had the least amount of change of the four herd units, and was not strongly associated with any explanatory variables. Historical aerial photographs were a useful tool in landscape monitoring, and the recovery of bighorn sheep may be further aided by managing anthropogenic activity in the landscape.

Preface

This work represents a collaborative effort on behalf of the people involved in the Sierra Nevada Bighorn Sheep Recovery Program (SNBSRP). The three interest groups that make up the SNBSRP include Dr. Tom Stephenson of the California Department of Fish and Game, Dr. Mark Hebblewhite and Lacey Greene, MSc, of the University of Montana, and Dr. Greg McDermid and Erin Latham, MGIS, of the University of Calgary. A past member of the project was Mike Dodd of the University of Calgary. This work represents a minor research component in the recovery of the Sierra Nevada bighorn sheep population, and began during the summer of 2008.

Acknowledgements

I would like to extend my thanks and appreciation to the support of everyone working on the SNSBP. I would like to thank Dr. Greg McDermid for his mentorship and guidance as a supervisor, teacher, and colleague. I would also like to thank Dr. Mike Gibeau with whom has provided me with countless opportunities over the past eight years in wildlife research. Through bears, berries, and b-tigers… Thank you for the encouragement and opportunity to pursue my Master’s degree at the University of Calgary.

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1.0 Chapter 1: Introduction

The bighorn sheep population in the Sierra Nevada (*Ovis canadensis sierrae*) was listed as an endangered species in 2000 (65 FR 20). The causes of the population decline have been attributed to illegal hunting (Advisory Group 1997, Wehausen and Hansen 1988), disease (Buechner 1960), and the direct and indirect effects of predation (Wehausen 1996). The vulnerability of the population is exasperated by low nutrition, environmental stochasticity, and anthropogenic disturbance (65 FR 20). The recovery effort on behalf of the California Department of Fish and Game and the SNBSRP may be further impeded by changes in the landscape over the last century.

The habitat of bighorn sheep overall remains intact and contiguous, and the sheep tend to prefer open terrain allowing for better visibility of predators (65 FR 20). Tree encroachment, specifically by single-leaf piñon (*Pinus monophylla*), has been documented in previously open habitat of the Sierra Nevada (Burwell 1999, Miller and Rose 1999, Gruell 2001, Romme et al. 2009), but its impact in bighorn sheep range specifically has yet to be investigated. The extent of encroachment has been associated with lower elevations in mesic and xeric sites depending on annual precipitation (Burwell 1999). Previous studies have used historical ground-based photographs (Gruell 2001), tree rings and fire scars (Miller and Rose 1999), and ground plots (Burwell 1999) to determine historical landscapes; however, historical aerial photographs taken in 1929 and 1944 may provide a unique objective record of historical vegetation patterns. The available archives in the Sierra Nevada region are limited in extent, but partial coverage of the eastern mountains suggests a potential for studying long-term landscape change in the bighorn sheep herd units.

Habitat encroachment and change-detection studies have utilized historical aerial photography in other areas, but there is a lack of consensus in the literature on how to perform a quantitative analysis using the principles of the scientific method. Although there are many constraints that limit the interpretation of historical datasets, their value in long-term monitoring and change-detection studies have not yet been fully realized.

1.1 Objectives

The principal goal of this research project was to evaluate the changes in Sierra-Nevada bighorn sheep habitat over the past 75 years using historical aerial photography. In working to achieve this goal, two main objectives were set:

- To review the literature pertaining to long-term (30-year-plus) landscape monitoring and remote sensing in order to determine the best practices for working with historical data sources, and
- To undertake a change-detection analysis of the Sierra Nevada using modern and historical aerial photographs.

A hypothesis related to the second objective based on previous literature suggests that changes in bighorn sheep habitat will be associated with low elevations, northern aspects, and north latitudes. The analysis will attempt to characterize the trend of tree cover change around the bighorn sheep herd units with substantial low elevation forest, and these results may assist managers of the Sierra Nevada Bighorn Sheep Recovery Program

(SNBSRP) in restoring lost or vulnerable habitat to further aid the recovery of the subspecies.

2.0 Chapter 2: Background

2.1 A Review of the Role of Remote Sensing in Long-Term Landscape Monitoring

Landscape monitoring is a valuable activity used to observe changes on the Earth since prehistoric times. Life on earth has responded to these changes, and in the last 160 years, the field of remote sensing has played a recognized role in vegetation monitoring (Dalke 1941, Greenwood 1957, Foran 1987), wildlife management (Leedy 1948), urban-interface development (Stone 1948, Gordon 1980), mining operations (Garofalo and Wobber 1974), encroachment and invasive species (Laliberte et al. 2004, Müllerová et al. 2005), erosion (Ries and Marzolff 2003) and fire disturbance (Wulder et al. 2009). Not only has remote sensing focused on observation for monitoring, but the application of new methods on old and current datasets have brought continuous improvement to the field (Cooke and Harris 1970, Johnson and Kasischke 1998, Rhemtulla et al. 2002, Rönnbäck et al. 2003, Coppin et al. 2004, Fraser, Olthof and Pouliot 2009, Kennedy et al. 2009, Linke et al. 2009, Townsend et al. 2009).

Several review papers have been written on the application of remote sensing in long-term landscape monitoring, but generally they are are narrow-focused and concentrate on topics such as aerial photography (Bowden and Brooner 1970, Fensham and Fairfax 2002), specific analytical strategies (Rönnbäck et al. 2003), digital change detection methods (Coppin et al. 2004), historical repeat photography (Kull 2005), protected areas (Gross, Goetz and Cihlar 2009), and change detection tools (Kennedy et al. 2009).

Kennedy et al (2009) has provided a strong recent synthesis, but was unable to adequately address the importance of early aerial imagery and other historical datasets, nor do the authors address the integration of datasets that would become necessary for monitoring across time periods spanning decades. Coppin et al (2004) considers the inclusion of multiple sources of imagery, but the review is restricted to digital change detection methods using satellite imagery. A literature review that summarizes the use of multiple generations of remotely-sensed data types across long, 30-year-plus time intervals does not currently exist.

The application of remote sensing for landscape monitoring is biased to the recent era of computer development and satellite technology. An early review by Cooke and Harris (1970) discussed remote sensing datasets and methods to date, and speculated on the future potential of "spacecraft" in landscape monitoring. In recent studies, the baseline state of the landscape is often restricted to the 1970s, when satellites designed specifically for earth observation became widely available (Jensen 2007). While many researchers have recognized the limitations of monitoring studies restricted to the satellite era, relatively few studies have made use of integrated data sources.

The three dominant eras of remote sensing include (i) ground-based photography, (ii) aerial photography, and (iii) satellite imagery. Ground-based photography dates back to the mid-1800s, although in many areas it is rare to find photographic coverage prior to the 1900s. These photographs were black and white and most often chronicled human settlements. They were also the only remote sensing data available until the advantages of air-borne acquired imagery from other sensor platforms were realized, such as hot-air balloons and blimps (Batut 1890, Ries and Marzolff 2003), as well as planes (Jensen 2007).

The earliest available archives of aerial photographs are from the 1920s. They are usually panchromatic, and their quality varies due to the new-but-ongoing development of film and camera technology at the time. While the emergence of colour and infrared film in the 1930s enabled new applications of aerial photography (Jensen 2007), the extra expense precluded its use in large-scale missions. Aerial photographs cover relatively large areas, and were often used for land management planning and agricultural development (Helms 2010). As aerial photographs became more common, satellite sensor development progressed throughout the 1970s.

Satellite imagery is perhaps the most variable of the three main sensor mediums and ranges from panchromatic high-spatial-resolution (very similar to historical aerial photographs) to multi- and hyperspectral low-spatial-resolution. The greatest advantage of satellite imagery is its wide spatial and temporal coverage of the earth’s surface. Photogrammetry using manual interpretation and stereo-parallax has been very successful in the past, but satellite imagery and the computer era have brought about new methods that may also be extended to analyzing historical remote sensing datasets.

For this review, long-term landscape monitoring will be defined as the repeated observation of a phenomenon over time intervals exceeding 30 years. By observing irregular trends in the landscape, management and planners may be able to intervene before such changes become irreversible; however, monitoring of the landscape using remote sensing requires planning and sorting through a wealth of available remote sensing data. The elementary question remains: What is the base-line land-cover state that we should strive to maintain? Remote sensing is not the whole answer, but in North America, significant anthropogenic change has coincided with the development of photography in the late 19th century. The historical remote sensing archive presents a unique opportunity that is currently not being used to its potential. This review will provide a synthesis on the use of remote sensing for long-term landscape monitoring, and will provide a break-down of trends through the major eras of remote sensing development. Further discussion will critique the current methods of long-term landscape monitoring as well as provide a status update and future potential of development in this discipline

2.1.1 The Development of Remote Sensing Through Time

In order to assess the role of remote sensing in long-term landscape monitoring, a thorough review of the literature has been compiled and synthesized in chronological order. Table 1 summarizes the relevant details of each specific study. The following sections will discuss many of these research articles and describe their contributions to landscape monitoring. They are meant to provide a comprehensive overview that will set the context for further discussion.

Table 1: A synthesis of literature representative of the trends and progress of remote sensing data utilized in long-term monitoring studies.

Reference			Data Type(s)	Imagery Resolution		Temporal Range of Study	Image Quality	Analysis Objective	Analysis Approach	Conclusions and/or Recommendations
Lead author	Year	Journal		Spatial	Spectral					
Dalke	1941	Journal of Wildlife Management	Aerial photographs	na	na	na	na	Monitoring recommendation; cover mapping wildlife at state level	Qualitative; observational, manual interpretation required	Cover map is created as example; for monitoring, recommends making several copies of traced maps for future use
Ives	1946	Journal of Geology	Aerial photographs (as secondary dataset)	na	Low; panchroatic	na	na	Investigative; characterizing glacial bastions	Qualitative; observational	Future glacial bastion locations could be identified with aerial photographs
Hoene	1946	American Forests	Aerial photographs	na	na	na	na	Change detection indicated how beaver dams had flooded surrounding forests causing damage	Qualitative; observational	Much damage had been incurred and beavers should be trapped and moved to higher elevations
Stone	1948	Geographical Review	Aerial photographs	Low; 1:30000 to 1:50000	Low; panchromatic	1941/ 1942	Low; unprocessed	Evaluation of dataset for assessing vegetation	Qualitative; observational	Vegetative keys created for further air-photo interpretation; Keys will be valuable in identifying land for settlement, planning for fire control, lumbering and/or

										mining.
Kerr	1952	Bulletin of the American Association of Petroleum Geologists	Aerial photographs (as second-ary dataset)	na	Low; panchromatic	Single date: 1934	Low; Unprocessed	Investigative; sand control in desert settings	Qualitative; observational	Various solutions for wind sand control given which are useful to military engineers and others for protection of military installations
Greenwood	1957	The Geographical Journal	Aerial photographs	na	Low; panchromatic	Single date: ~1947-1948	Low; unprocessed	Investigative; inferring the development of vegetation patterns	Qualitative; observational	Peculiar patterns of vegetation observed in aerial photographs and land change inferred from ground-based validation
Welch	1966	The Photogrammetric Record	Aerial photographs	Moderate; 1:16000	High; panchromatic, false colour, true-colour, infrared	Single date: 1956	Low to Moderate; Unprocessed	Evaluation of datatsets; which dataset is best for interpretation of glaciated areas	Qualitative; observational	The colour films were best due to ability to discern vegetation and moisture, and infrared was the worst of the 4
Haralick	1973	IEEE Transactions on Systems, Man, and Cybernetics	Photomicrograph, aerial and satellite (MSS) photographs	Low; 1:20000, 80m	Low to Moderate	na	Low; Unprocessed	Evaluation of method; textural features for classification	Quantitative; pixel-based	Accuracy results were 82-89%; 7 land-use classes; texture has wide ranging classification applicability
Garofalo	1974	Photogrammetria	Aerial photographs	Low to Moderate	Low to Moderate	Moderate; 1935-1971	Moderate to High; Unprocessed	Evaluation of data and change detection; environmental impacts of clay mining	Qualitative; observational	Colour photographs best for determining mining effects but requires on-ground sampling for best results; photographs

										will aid in minimizing environmental damage
Reeves	1976	Journal of Wildlife Management	Satellite (ERTS/Landsat-MSS, TIROS, VHRR)	Low; 80m	Low to Moderate	High; 1973-1974	Moderate; Unprocessed	Monitoring and evaluation of dataset; arctic habitat and goose production	Qualitative; observational	Late disappearance of snow may limit goose reproduction; satellite sensors are incorporated in annual monitoring
Nagao	1979	Computer Graphics and Image Processing	Aerial photographs	Moderate; 1:10000	Moderate	na	Low; Pre-processing (smoothing filter)	Evaluation of method; object-based classification of suburban area	Qualitative evaluation; object-based	Most objects successfully recognized but many objects unrecognized; Useful tool for analysis of complex suburban areas
Gordon	1980	Remote Sensing of Environment	Satellite (LandsatMSS) and air-photos	Low; 80m	High	High (1973, 1975)	Moderate; Unprocessed	Evaluation of dataset; determining suitability to monitor land-use change	Quantitative; manual classification	Large errors resulted in urban categories; future application will be improved when the registration accuracy of the data improves
Robinove	1981	Remote Sensing of Environment	Satellite (LandsatMSS)	Low	High	High; 1972-1976	Low; Pre-processing (atmos. Correction, MSS calibration, sun angle)	Evaluation of method/dataset for arid land monitoring	Quantitative/qualitative; observational, regression	Increased albedo change may indicate degradation, and changes may be correlated with erosion, soil moisture, density of vegetation (most relating to moisture); further tests in hot deserts needed
Howarth	1983	Remote Sensing of	Satellite (Landsat	Low to Moder-	Low/High; panchro-	Moderate; 1974-	Low; Pre-process-	Evaluation of method for	Qualitative; observational	“The ability to overlay imagery from two

		Environment	MSS), aerial photographs to qualify	ate; 80m, 1:10000	matic	1978	ing (“digital image correction system” ortho-rectifier)	monitoring of Landsat urban environment		dates, to generate image enhancements, and to display them on a CRT monitor were essential attributes of the system for undertaking the study”; the band ratios only emphasized major changes, but digital enhancements could be use instead of classification for monitoring urban areas
Bryan	1984	Remote Sensing of Environment	Satellite (Seasat SAR)	High; 25m	Low; Black and white	High; June-October 1978	High; Unprocessed	Evaluation of dataset for change detection with Seasat synthetic aperture radar	Qualitative/quantitative; observational	SAR emphasizes geometric form and roughness and guidelines are presented for using SAR in different landscapes
Foran	1987	Remote Sensing of Environment	Satellite (LandsatMSS), aerial photographs	Low to High: 80m, 1:3000	High/unknown	High; 1980-1984	Moderate; Unprocessed (no atmos correc, but band index)	Monitoring change of pastoral landscapes	Quantitative; manual classification, regression	Imagery came as “computer compatible tapes”. Prediction of change by vegetation cover was difficult due to rainfall variation or change at the sub-pixel level. Coarser NOAA imagery may be more suitable at the regional level.

Pinty	1992	Vegetation	Satellite (NOAA/ AVHRR)	Low; 4km	High	na	Moderate; Unprocessed	Evaluation of method for monitoring global vegetation with new non-linear index similar to NDVI	Quantitative; investigative	Other indices are sensitive to atmospheric effects, but new index is not, but maintains information of veg cover
Guinet	1995	Polar Biology	Satellite (SPOT), aerial photos	High; 20m	High	Moderate; 1982-1988	High; Pre-processing (Registration, normalize-ation)	Evaluation of dataset and monitoring; using SPOT imagery for penguin counts	Quantitative; pixel-based analysis	Without ground data, hard to validate penguin presence/absence; based on surface area, 1 mill penguins breed at location with surface area increase since 1962
Schlesinger	1996	Global Change in Biology	Aerial photographs and satellite (Corona)	na	na	Low; 1943, 1974, 1977, 1987, 1992	High; unprocessed	Change detection of vegetation in response to climate	Quantitative; tree crown counts	Woody vegetation has not responded to climate change
Thomlinson	1996	Biotropica	Aerial photographs	Moderate; 1:20000	Low; black and white	Low; 1936, 1964, 1988	High; unprocessed	Monitoring of land use	Quantitative; manual delineation	An increase in forest and much human/agricultural change;
Mast	1997	Forest Ecology and Management	Aerial photographs	High; 2.5m	Low	Low; 1937, 1941, 1953, 1988/90	High; Pre-processing (filter)	Change detection of tree invasion	Quantitative; pixel-based (Boolean)	16-19% change and rate of expansion greatest on north-facing moist site (Colorado); corresponds to favourable climate
Johnson	1998	International Journal of	Satellite (Landsat	Low	High	Moderate; several	Moderate; Pre-	Evaluation of method; change	Qualitative; observational	CVA useful for when change is unknown,

		Remote Sensing	TM, Landsat MSS)			datasets 1974-1992	processing (Registration, normalizeation)	vector analysis for monitoring of land cover/condition		when objects have high spectral variability, and changes in both land cover/condition have occurred; CVA important for long-term monitoring in multispec data
Rhemtulla	2002	Canadian Journal of Forest Research	Repeat photography and aerial photographs	Moderate; Aerial photographs 1:20000	Low; black and white	Moderate; 1915, 1949, 1997	High; Unprocessed	Evaluation of method and change detection of vegetation	Quantitative; manual classification	Shift towards late successional vegetation and increase of crown closure in conifer stands; results may help to establish restoration goals in ecosystem
Ries	2003	Catena	Aerial photographs from blimp	High; 1:100 to 1:10000	Moderate; RGB and infrared	High; Three years, 1995-1998	High; Unprocessed	Monitoring of gully erosion	Quantitative; manual interpretation	Some lateral change but most at gully bottom; blimp bridges the gap between aerial and ground photography
Corripio	2004	International Journal of Remote Sensing	Ground-based photographs	na	Moderate	na	High; Pre-processing (ortho-rectification, histogram correction)	Evaluation of method to determine snow surface albedo with photos	Quantitative; pixel-based analytical	Georeferencing image successful (better when taken at high points), and the spatial distribution of albedos had good agreement with *in situ* measurements; further work expected
Laliberte	2004	Remote Sensing of	Aerial photograp	High; 0.6m	Low to High	High; several	High; Preproces	Change detection of shrub	Quantitative; object-based	Shrub cover increased and grass decreased;

		Environment	hs, satellite (Quickbird)			dates from 1937 to 2003	sing (ortho-, registration)	encroachment in New Mexico		object-based is improvement over pixel; despite problems, historical aerial photos valuable
Manier	2005	Landscape Ecology	Aerial photographs, second-ary satellite data (Landsat)	Moderate; 1:20000, 1:30000	Low to High	Low; 1937, 1966, 1994	High; Preprocessing (ortho, registration)	Change detection of woody and herbaceous vegetation in Colorado	Quantitative; manual classification, regression	Minor net change <2%; increase of forest at low elevations, decrease at high; change in vegetation varied temporally and spatially
Fensham	2005	Journal of Ecology	Aerial photographs	Low; 1:25000-1:40000	na	Low; several dates from 1945-1999	Moderate; Unprocessed	Change detection of rainfall, woody veg and land use	Quantitative; regression using 15 land cover types by manual classification	Rainfall main explanatory variable for over-storey cover; important interactions of rainfall and density dependence
Müllerová	2005	Journal of Applied Ecology	Aerial photographs	Low to Moderate; 1:10000 to 1:27000	Low to Moderate	Moderate; several dates from 1947-1996	Preprocessing (ortho-rectification, enhancements)	Monitoring of invasive plant species spread	Quantitative; manual and pixel-based classification, as well as ANCOVA regression	Pastures and fields accounted for 85% of the invasive plant cover with avg rate of spread 1261 m^2 yr^{-1}; areas more susceptible to invasion may be identified with aerial photographs
Zier	2006	Forest Ecology and Management	Repeat photography	na	Low; Black and white	Irregular; since 1878 to 1948	High; Unprocessed	Change detection in forested landscape	Qualitative; observational	Conifer and deciduous stands increased in extent largely due to recovery from past disturbances; loss of native grasses

Garrigues	2006	Remote Sensing of Environment	Satellite (SPOT)	Moderate /High (20m)	Moderate	na	Moderate; Pre-processing (cloud mask)	Investigates spatial hetereogeneity at the landscape scale with variograms	Quantitative; pixel-based variogram analysis	The spatial scale of vegetation was 100m in complex landscape; variograms are powerful method for characterizing the landscape
Roush	2007	Arctic, Antarctic and Alpine Research	Repeat photography	na	Low; Black and white	Irregular; since 1910 to 1932	High; unprocessed	Evaluation of method and change detection of alpine treeline ecotone	Quantitative; manual classification of change (no accuracy)	Tree cover increased in 10 of 12 photo pairs by 60%; ground control points would remedy some of the issues associated with scale in the photos
Weisberg	2007	Rangeland Ecology and Management	Aerial photographs	High; 1m	Low, Moderate	Low; 1966-1995	High; Preprocessing (ortho, coregis, normalize)	Change detection of piñon-juniper woodland expansion	Quantitative; object-based classification	11-33% change with increased woodland in low elev, low slope and high mesic aspects dep on scale
Salehi	2008	Land Degradation and Development	Aerial photographs	High	Low	Low; 1969, 1993	Moderate; Preprocessing (ortho, coregis)	Change detection of land cover, Iran	Quantitative; manual interpretation of tree counts	Forest has increased though crown cover and large trees are stable; natural regeneration rare
Nagler	2009	Remote Sensing of Environment	Aerial photographs and satellite (Landsat/ MODIS) as secondary datasets	High/ Moderate	Low and High	High; 1992-2006	High; Pre-processing (ortho-rectification)	Monitoring of hydrology and vegetation in riparian corridor	Quantitative; manual classification and further pixel-based processing	Regional source of water is from aquifer fed by Mexico and US; cottonwood/willow have regenerated but subject to human disturbance; monitoring and

										restoration is needed to maintain habitat value
Pringle	2009	Journal of Applied Ecology	Aerial photographs, satellite (Quickbird)	High	Low and High	Low; 1941, 1971, 2006	High; Preprocessing (ortho)	Evaluation of method and change detection of endangered sp habitat	Quantitative; object vs pixel based classification	Object-based outperformed pixel in accuracy; decrease in bare rock and increase in tree-canopy; removing vegetation good for snakes
Platt	2009	Forest Ecology and Management	Aerial photographs	High	Low/ Moderate	Low; 1938/40-1999	High; Preprocessing (ortho, registration)	Change detection of tree cover in Colorado	Quantitative; object-based classification, basic stats	Change 0-13% mostly on south slopes and low elevations
Wulder	2009	Remote Sensing of Environment	Satellite (Landsat, LIDAR)	Moderate	Moderate	1997-2002	High; Pre-processing (TOA, co-registration)	Dataset evaluation and change detection of forest structure pre- and post-fire	Quantitative; pixel-based indices and patch-based analysis, further basic statistics	Post-fire and pre-fire conditions had variable relationships; LIDAR was good for forest structure information in post-fire conditions
Michel	2010	Applied Vegetation Science	Repeat Photography	na	Moderate	Low; 1986-2007	High; Unprocessed	Evaluation of method; grid- vs. object-based change in plant communities	Qualitative; object-based and manual classification	Grid technique appeared more robust; both grid- and object- have potential for quantitative vegetation monitoring

2.1.2 Ground Based Photography Era

Historical ground photographs from the 19th and early 20th century typically portray the hardships and triumphs associated with early frontier development. Photographers chronicled the path of the early settlers, and many archives include magnificent scenery points and geological features that may not be intact today. For example, an archive from the Sierra Nevada is dated from 1849 during the period of Euro-American settlement (Gruell 2001), but prior to the development of conservation areas and widespread livestock grazing (Wehausen et al. 1987). Ground-based photography expeditions were generally not as intensive in coverage compared to what aerial photography expeditions would become, but in 1915, a Canadian surveyor named Bridgland set out for the express purpose of mapping the Rocky Mountains by taking photographs of the landscape from the highest mountain peaks (Rhemtulla et al. 2002).

Historical photographs were typically taken from a non-metric camera, and while they are considered a remote sensing dataset, they differ from aerial photographs in that they were typically taken from extreme oblique angles. Nonetheless, they may show a high amount of detail, and therefore are a valuable dataset that may be used to depict the historical landscape.

2.1.2.1 Characteristics

Historical ground-based photography is often utilized by modern researchers using repeat-photography techniques. Photographs are re-taken from the same photo-point to replicate the scene in order to make a direct comparison of change. For example, Gruell (2001) studied 84 sets of historical photographs in the Sierra-Nevada from 1849 to 1920 and demonstrated forest transition and change. He was unable to quantify the change or provide a mechanism for it, but he suggested that the open and variable forest structure evident in the historical imagery resulted from regular fire disturbance (Gruell 2001). Similarly, Rhemtulla et al (2002) studied the Bridgland expedition photographs from the Canadian Rockies in 1915 and found that vegetation had transitioned to a late-successional state with increasing crown closure in conifer stands. Until recently, though, it has been difficult to make a quantitative analysis of vegetation change in such photographs due to their non-systematic geometry and issues of geo-referencing. Corripio (2004) was able to successfully orthorectify oblique photographs using a viewing transformation of a 10-meter DEM. Advantages of working with photographs taken from high points, such as mountains peaks with steep viewing angles, were noted, although high-resolution DEMs would have better application (Corripio 2004).

Most studies that use repeat photography remain qualitative and observational in an attempt to describe vegetation change (Gruell 2001, Rhemtulla et al. 2002, Zier and Baker 2006), and they often use visual assessments to determine classification accuracy (Michel 2010). However, simple principles in study design enabled Roush et al (2007) to perform a manually intensive quantitative assessment of vegetation change using historical photographs. The study acknowledged and addressed many of the issues associated with oblique photographs, including the interpretation of vegetation from approximately the same distance to the photo-point in order to mitigate the issue of foreground objects appearing larger than background objects. Although manually intensive, the study analyzed 12 photo pairs from Glacier National Park in Montana, and concluded that the treeline ecotone increased by an average of 60% in 10 of the 12 pairs since the 1920s. It was difficult for this study to acquire photographs with the necessary terrain attributes – 2000 photographs were originally reviewed – but a clear trend was demonstrated.

2.1.2.2 Summary

There remains significant potential in analyzing historical ground-based photographs in a quantitative fashion that will lend them useful to evaluating the historical landscape. The concern of using historical photographs is the variability in the landscape, and that inference on change and landscape condition will be limited. However, variability in the environment is expected and acknowledged in every remote sensing dataset. Historical datasets will not be applicable to all monitoring studies, but they are under-utilized at present.

The integration of methods by Roush et al (2007) and Corripio (2004) will increase the potential of historical ground-based datasets in long-term monitoring studies. Further study may be required to investigate the sensitivity of grid cell size and change detection in the sampling design, but considering ground-based photography as a valuable remote sensing dataset is being realized in the landscape monitoring community. Ground-based photographs may be the most interesting of all remote sensing data because of their historical reach through time.

2.1.3 Aerial Photography Era

Aerial photograph missions began as part of military mapping and exploration endeavors (Jensen 2007). The field quickly evolved with the help of commercial enterprises producing film and cameras as well as improved sensor platforms to have wider applications for domestic and international reconnaissance (Jensen 2007). The high-spatial-resolution aerial imagery resulting from these early missions have led to monitoring the landscape in several ways. Wide-scale mapping of agriculture was undertaken by many government agencies such as the Soil Conservation Service in the United States in the late 1920s (Helms 2010). Military reconnaissance missions utilized aerial photography during the two World Wars (Jensen 2007). Aerial photographs were not often used beyond agricultural and military applications (Jensen 2007), but a few studies used them as an investigative tool to survey glaciers (Ives 1946), flood damage (Hoene 1946), sand dune and vegetation patterns (Kerr and Nigra 1952, Greenwood 1957). It is appropriate to note that historical aerial photography is not consistently comparable to modern aerial photography. Aerial photographs taken more recently are often high-spatial-resolution multispectral images with high registration accuracy, and they still are prone to shadow and distortion effects, though to a lesser degree than historical datasets.

2.1.3.1 Characteristics

The earliest references of using historical aerial photographs for monitoring studies extend back to the 1940s, although many of these early studies used the photographs for observation as secondary datasets rather than primary photo-interpreted analysis (Dalke 1941, Ives 1946, Hoene 1946, Stone 1948, Kerr and Nigra 1952, Greenwood 1957, Welch 1966, Garofalo and Wobber 1974). One of the very first studies that recognized the monitoring potential of airborne-based photographs advised, “it is best to make the tracing [of land-cover maps,] and to print a number of copies” (Dalke 1941, p.104). Morgan (2006) reviewed the application of historical aerial photographs for ecosystem monitoring and provided a useful table outlining general characteristics (Table 2). As previously mentioned, historical imagery has high spatial resolution and is usually available as panchromatic. However, the imagery often suffers from major spatial and radiometric distortions, and may be unpredictable for temporal consistency at a daily and annual, and possibly decadal scale (2).

Table 2: Historical digitized imagery and its advantages and disadvantages (adapted from Morgan 2006).

	Advantages	Disadvantages
Temporal	Long time series	Lack of repeat imagery at volume, time of day (sun angle and shadows)
Spatial	1:20000, High-resolution <1meter	Restricted locations, registration errors during pre-processing
Spectral	Panchromatic	Black and white
Radiometric	Typically >8-bit	Atmospheric noise and illumination inconsistency

The high spatial resolution of aerial photographs has allowed for changes in the forest to be observed using tree counts (Schlesinger and Gramenopoulos 1996, Herwitz, Slye and Turton 2000, Salehi, Wilhelmsson and Söderberg 2008). Pixel-based analyses have been used and include but are not limited to: textural analysis (Haralick, Shanmugam and Dinstein 1973, Hudak and Wessman 2001), variogram analysis (Garrigues et al. 2006) wavelet analysis (Strand et al. 2006) and classification based on spectral components and indices (Howarth and Boasson 1983, Pinty and Verstraete 1992, Kadmon and Harari-Kremer 1999, Okeke and Karnieli 2006, Wulder et al. 2009). Object-based classification has been recently popular, although manual interpretation of historical aerial imagery has been utilized more frequently (Thomlinson et al. 1996, Cameron et al. 2000, Eckhardt, van Wilgen and Biggs 2000, Bowman, Walsh and Milne 2001, Manier et al. 2005, Thomson et al. 2007, Weisberg, Lingua and Pillai 2007, Romme et al. 2009). Object-based analysis, which is more similar to manual interpretation methods, has been popularized to be advantageous over pixel-based classification of historical imagery (Laliberte et al. 2004, Morgan 2006, Zomeni, Tzanopoulos and Pantis 2008, Platt and Schoennagel 2009, Pringle et al. 2009). The various methods have had moderate success, but it may be difficult to determine their applicability because of several factors.

Object-based analysis of historical aerial photographs is still susceptible to misregistration errors which are prominent in historical imagery. Another problem realized in object-based analysis is the limitation of segmentation algorithms on panchromatic imagery with illumination inconsistency (Morgan 2006). In multispectral imagery, the increased number of bands allows for greater segmentation options, which leads to greater control over scale. The object-based analysis of historical aerial imagery performed by Platt and Schoennagel (2009) seemed to be as intensive as a manual interpretation. In some circumstances, manual interpretation may be more appropriate, but the scale of analysis is not as easy to enforce in delineating polygons over using a software. Many studies circumvent the issue by establishing guidelines for polygon sizes delineated at certain viewing magnifications, along with change thresholds (Callaway and Davis 1993, Herwitz et al. 2000, Thomson et al. 2007).

Interpreting historical imagery is inherently difficult because of the lack of ground-observation data required to validate air-photo interpretation. The minimum mapping scale for interpreting vegetation is very difficult to define in historical imagery because of distortions and illumination inconsistencies. This has implications for studies seeking to identify mixed species or structure categories. Shrubs relative to trees have been consistently difficult to interpret with accuracy, even in modern datasets (Kadmon and Harari-Kremer 1999, Augustin, Cummins and French 2001, Fensham and Fairfax 2002, Laliberte et al. 2004, Okeke and Karnieli 2006). The ability to use stereo-parallax has allowed heights of objects to be measured accurately, although the results of digital stereo interpretation has not been observed in the literature (Fensham and Fairfax 2002).

2.1.3.2 Summary

A constraint of using historical imagery for landscape monitoring is the lack of field observations to validate the data. Another potential consequence of using historical imagery is that it may not sufficiently encapsulate the targeted object on the landscape, for instance the distribution of a flowering plant in a wide-landscape photograph, thereby resulting in an ad-hoc approach to incorporating historical data into long-term monitoring. However, explicitly stating and acknowledging reasonable assumptions and limitations and quantifying the accuracy of results should help bring greater value to these data. Many studies use modern ground observations to calibrate or validate the historical dataset, and make the false assumption that the historical interpretation is comparable (Laliberte et al. 2004, Zomeni et al. 2008, Brook and Bowman 2006). Other studies fail to perform any sort of accuracy assessment (Manier et al. 2005), and another study validating photo-interpreted imagery chose to "[exclude] a small minority of randomly generated points that fell in areas where we were not confident in our assessment" (Pringle et al 2009, p. 547). Another issue is that there is a lack of standards for assessing the accuracy of object-based classifications. The accuracy of the vegetation classification in object-based analyses may be considered separate from the accuracy between two object delineations. Objects, therefore, may be compared using spatial information, such as shape, size, distance vectors, vertices, and centroid points (Clinton et al. 2010). One of the major researchers in this field recently composed a review of object-based analysis and could only identify validation assessments as a "hot" research topic (Blaschke 2010). Object-based classification cannot be assumed to be the most efficient processing; it requires a significant time investment, including learning how to expertly use the specific software for analysis.

Many studies that analyze historical imagery may be testing methods on very small datasets, and an analysis looking at shrub encroachment in flat terrain may be less complicated than looking at shrub and forest change in a mountainous landscape. Image quality is rarely consistent and differences in illumination have been found to complicate many analyses, such as texture (Haralick et al. 1973). The mis-registration error of historical datasets once orthorectified and/or co-registered may still exceed 10 meters (Marrs and Hicks 1986, Hudak and Wessman 1998, Kadmon and Harari-Kremer 1999, Manier et al. 2005, Brook and Bowman 2006, Platt and Schoennagel 2009). The horizontal accuracy found by Barrette et al (2000) in identifying wetland boundaries on large-scale colour aerial photographs was 3.4 meters. Therefore, traditional change-detection methods that are readily applicable to satellite imagery may not be suitable for use with historical imagery.

Stereo-photogrammetry of historical imagery may be required in further studies to improve the accuracies of interpreting vegetation and object classes due to the absence of ground-based measurements. Currently, the best practices for interpreting historical imagery may include manual and point-based sampling. Aerial imagery represents the largest remote sensing dataset, and it would be ill-advised to exclude them from long-term landscaping monitoring.

2.1.4 Satellite Era

After World War II and the failed quest for peaceful reconnaissance of air-photo missions into neighbouring countries, orbiting remote sensors became an important part of the space frontier. The Sputnik satellite was launched in 1957 by the Soviet Union, followed by the Corona satellite by the US in 1959,which produced its first imagery in 1960 at 40-foot spatial resolution (Jensen 2007). The popular remote sensing journal "Remote Sensing of Environment" published its first issue in 1969, and the first civilian earth-observation satellites were launched by the United States in the 1970s (Jensen 2007). The Landsat Multispectral Scanner (MSS, Landsat-1), previously called the Earth Resources Technology Satellite (ERTS), began this paradigm shift, and held four spectral bands with a spatial resolution of 68 by 83 meters (Jensen 2007). Six additional missions have followed, and Landsat has been the primary sensor for terrestrial monitoring, primarily because of its spatial and spectral suitability for consistently observing various environments on the earth's surface. Landscape monitoring using radar may not be as common primarily because its advantages are in ice- and snow-covered landscapes. It was used in a study from the 1970s to census snow conditions and habitat for geese in the arctic (Reeves, Cooch and Munro 1976). Soon other satellite sensor systems began to appear in landscape monitoring studies, such as high spatial resolution SPOT and Quickbird, MODIS and more recently, Lidar.

2.1.4.1 Characteristics

Early monitoring studies using exclusively satellite data were analyzed similar to aerial photographs . Preprocessing of the data was either absent or minor, probably due to the constrained technological capabilities at the time. Haralick (1973) performed perhaps one of the first quantitative assessments using both the Earth Resources Technology Satellite (ERTS) and aerial photographs to investigate the use of texture analysis in identifying land-cover classes of Virginia and California, including residential, swamp, marsh, scrub, wood, and others. The aerial photographs and satellite imagery had 82% and 83% classification accuracies, respectively. The application did not require any necessary preprocessing, although gray-tone normalization was suggested for further exploration. Reeves (1976) utilized the Landsat MSS, the Television Infra-Red Observational Satellite (TIROS), and the Very High Resolution Radiometer (VHRR) sensors to look at nesting locations for arctic geese from 1973 and 1974 in locations such as Greenland, the U.S.S.R, and Canada. Goose production was associated with early snow and ice disappearance from the arctic, and predictions for the reproduction success of the following 1975 season were made and were validated. The potential of satellite data was being realized, although graduating to quantitative analysis required some intermediate steps. Gordon (1980) evaluated the MSS dataset and its value in monitoring land-use change in Ohio. Registration errors complicated the classification process, and it was suggested that the dataset would be more valuable when the registration accuracy improved. Preprocessing methods must have been realized as a necessary step in many studies, and Robinove et al. (1981) was able to correct for atmospheric effects in research involving albedo monitoring. A difference image between dates of 1972 and 1976 indicated possible change areas that were qualitatively analyzed (Robinove et al. 1981).

The use of satellite data for monitoring became more heavily used as the resolution and errors were improved upon. Early on, high-spatial-resolution aerial photographs were often used to evaluate the accuracy of satellite sensors (Gordon 1980, Howarth and Boasson 1983, Guinet, Jouventin and Malacamp 1995), since satellite sensors were often lacking in this respect. Foran (1987) investigated change of pastoral landscapes from 1980 to 1984, but found that the 80-meter-resolution Landsat MSS sensor might not have had the resolution necessary to study vegetation change in response to rainfall. Texture analysis was continually used as a means of studying various remote sensing datasets, and other pixel-based classification procedures were being performed on satellite imagery. Although object-based classification procedures had been tested on aerial photographs, the processing requirements seemed to hinder the analysis until the technology was able to catch up. As a note that observes the processing capabilities at the time, Howarth and Boasson (1983) remarked: "The ability to overlay imagery from two dates, to generate image enhancements, and to display them on a CRT monitor were essential attributes of the system for undertaking the [monitoring] study."

2.1.4.2 Summary

Many monitoring or change-detection studies that have used satellite imagery exclusively were testing new methods or datasets (Leonard Bryan and Clark 1984, Pinty and Verstraete 1992, Johnson and Kasischke 1998, Wulder et al. 2009). Such studies demonstrate small examples of how they may be incorporated into long-term monitoring initiatives. The advantages of working exclusively with satellite data are the predictability of the datasets and validated methods which have generally been accepted in the remote sensing community. The best practice for using satellite imagery in long-term monitoring studies is to take advantage of the resolution and accuracy of current datasets, but to incorporate historical imagery at least for a baseline reference (Nagao, Matsuyama and Ikeda 1979, Schlesinger and Gramenopoulos 1996, Laliberte et al. 2004, Manier et al. 2005, Nagler, Glenn and Hinojosa-Huerta 2009).

2.1.5 Other Remote Sensing Sources

Remote sensing imagery has been taken from the ground, airplanes, and satellites, but innovation has not been limited to these perspectives. Kites (Aber, Aber and Pavri 2002), hot-air balloons and blimps (Batut 1890, Ries and Marzolff 2003), remote-controlled helicopters (Wester-Ebbinghaus 1980) and pigeons (Verhoeven 2009) have all been used as sensor platforms for remote sensing imagery. Photographs resulting from a small camera mounted onto a pigeon, however, would have been of limited use for surveying. These sources of imagery are unlikely to be of us for long-term landscape monitoring as they generally occur at a very small scale.

2.1.6 Discussion

There has been an increasing emphasis on using satellite data for long-term monitoring studies. Several researchers have developed intricate and advanced monitoring protocols that are a testament to innovation and integration of methods and datasets (Fraser et al. 2009, Linke et al. 2009, Townsend et al. 2009). However, historical ground-based photography and aerial photographs have so far not been integrated into such monitoring frameworks because of their inconsistencies in temporal and spatial coverage, as well as the tedious processing methods required for interpretation. In the last 15 years, significant progress has been made in developing quantitative methods for interpreting historical datasets. The detail may not be to the consistency of current satellite imagery, but these data may be one of the most unique historical archives available, and it should be used to its potential in long-term landscape monitoring studies.

2.1.6.1 Dominant Trends

The trend of using remote sensing data in long-term monitoring may be further understood by examining each era independently. Ground-based photographs have been used occasionally in landscape monitoring studies, but the recent development in analysis techniques has allowed for quantified results that set a standard for the repeatability of methods, whereas past studies have used observation to make inferences of the landscape. However, the trend of using historical aerial photographs in landscape monitoring has been less progressive. Several influential studies have critical faults that have been observed to propagate in the literature, such as the lack of secondary validation on the interpretation of historical datasets. The incorporation of satellite imagery however has been the most progressive due its dominance by frequency in the literature. Therefore, the utilization of remote sensing data for long-term monitoring may be hindered due to a lack of progress in analyzing historical aerial photography.

2.1.6.2 Methods and Misconceptions

The methods and misconceptions for each remote sensing era are not uniform, but they do exhibit commonalities. The goal in the development of new processing methods for all three eras seems to be for automation, but automation is less refined for historical aerial and ground-based photography. A misconception of ground-based photography is its lack of relevance in broader large-scale monitoring studies. Although it may be limiting in certain applications (e.g. Nagel and Taylor (2009)), others (e.g. Molnia (2008)) have found it to be important and complementary to other remote sensing data sources.

The methods employed in the analysis of historical aerial photographs are inconsistent, but also tend to be dependent on the quality of the imagery. Therefore, object-based, pixel and manual methods may be applied in certain contexts. The principles of remote sensing must still be exercised in the analysis of historical imagery, although this seems to be a general misconception in the literature. The lack of validation on the historical aerial photographs was previously mentioned, but other issues have been identified, such as the lack of acknowledgement in the issues of re-sampling moderate resolution digital elevation models (DEMs) to correspond with a study's high resolution imagery (Mast, Veblen and Hodgson 1997, Kadmon and Harari-Kremer 1999, Pringle et al. 2009). In the common circumstance of data sources with varying resolutions, Weisberg et al (2007) chose to acknowledge the resolution mismatch rather than resample to a higher resolution. Another problem in the literature analyzing aerial photography is discerning shrubs from other vegetation (Kadmon and Harari-Kremer 1999, Laliberte et al. 2004, Okeke and Karnieli 2006), and identifying complex vegetation classes (Augustin et al. 2001). Certain limitations of historical imagery cannot be avoided, but it is important to acknowledge them and state the assumptions before undertaking the analysis. Cooke and Harris (1970) observe that "…advances in technology still outpace the experiments in its use" (p. 20). Unfortunately a lack of technology cannot be the scapegoat in the interpretation of historical imagery, but perhaps the automation of interpreting satellite imagery has jaded the scientific community, and manual interpretation is now considered to be an unrefined methodology. The techniques for incorporating satellite imagery into landscape monitoring are more standardized, but the issue of restricting the monitoring time-frame to the satellite era is inherently short-sighted and rather un-accommodating for the inclusion of historical imagery sets, as previously suggested in the quest for automated procedures.

2.1.6.3 The Integration Necessity of Data Sources

In long-term monitoring studies, it is important to be confident in the analysis of all the datasets utilized. In the past, non-empirical studies have created problems in the literature by propagating misconceptions in the scientific community, such as the un-proven assumptions of the historical fire regime in western North America revealed by Romme et al (2009). It is critically important that change-detection and monitoring studies using historical data adhere to the principles of the scientific method. Many of the change detection studies encountered in this review did not validate the outcome of change. Without ground-based observations, historical datasets should be interpreted by more than one person and/or method. Other literature sources may help to validate the results (Bowman et al. 2001), although Weisberg et al (2007) found that their results contradicted the mainstream literature.

Long-term monitoring studies should benefit from a number of data sources. Several studies observed in this literature review used either a combination of ground-based and aerial photography (Rhemtulla et al. 2002, Nagel and Taylor 2009), or aerial photography and satellite imagery (Gordon 1980, Howarth and Boasson 1983, Foran 1987, Guinet et al. 1995, Schlesinger and Gramenopoulos 1996, Laliberte et al. 2004, Manier et al. 2005, Nagler et al. 2009, Pringle et al. 2009). However, a dominant study that employed all three forms of remote sensing data has not taken place. The review paper written by Cooke and Harris in 1970 exemplified the excitement of the incoming satellite era (Cooke and Harris 1970) but they could not know or realize the possibility that ground-based and aerial photography data would become marginalized in the future remote sensing literature. Perhaps the absence of integrating historical remote sensing datasets with current satellite technology into long-term monitoring studies may be due to the lack of awareness of these historical sources. Molnia (2008) acknowledged the value of the historical remote sensing record for glacier monitoring, and indicated through example of photographic sequences how rapid changes of glaciers were apparent in the landscape . Glaciers may be the proverbial *charismatic mega-fauna* of the geologic world, and they have benefited from the long-term focal interest by many geologists, but they are an example representing the benefits of long-term monitoring: glacial recession has been used as indicator of climate change and warming temperatures (Haeberli et al. 2007).

The realization of the availability of historical data may require a serendipitous conversation between a historian and a landscape ecologist or manager, but during this research, one specific area in the United States has been identified as a prime candidate for the role of an influential long-term monitoring study. Colorado has been observed to be a focal centre for past historical remote sensing research (Mast et al. 1997, Manier et al. 2005, Platt and Schoennagel 2009). It may present an excellent candidate area for incorporating historical data into a long-term monitoring study. For example, Zier and Baker (2006) analyzed ground-based photographs in the San Juan Mountains of west-central Colorado, while Manier et al (2006) analyzed historical aerial photographs for vegetation and canopy dynamics, the distance of separation of the two studies only being 150 kilometers. Both studies focused on different time eras (1878-1948, 1937-1994), but similar results were found and noted increasing conifers in deciduous stands with obvious signs of anthropogenic disturbance. The integration of these two data sources could be a precursor to an interesting study of long-term vegetation dynamics and human settlement.

The incorporation of historical remote sensing data is not necessarily to encourage restoration and revert back to the historical landscape condition, but through acknowledging the historical context, we achieve better understanding of the landscape. Past disciplines including climate change research, endangered species protection, and sustainable development have benefited from the utilization of remote sensing as a tool, but the new challenge may be to compile what is known and employ active management as part of long-term studies.

2.1.7 Summary

The current trend of incorporating remote sensing imagery into long-term monitoring studies leaves something to be desired. Long-term monitoring studies have power in numbers: more sources help to validate trends, explore small- and large-scale processes, as well as they help extend the historical reach in time. This work has reviewed the role of remote sensing, and has acknowledged the current limitations of compiling and integrating the historical and satellite datasets into a robust long-term study. A strong influential study is needed to set a standard for future studies to follow, and the repeat analysis of historical data should be encouraged in order to make such progress and find consensus.

2.2 Bighorn Sheep of the Sierra Nevada

The bighorn sheep population of the Sierra Nevada, hereafter sheep, was listed as an endangered species in 2000 after being reduced to less than 100 individuals in the 1990s (Torres, Bleich and Wehausen 1994). The population once occupied a 250 kilometer stretch of the mountain range, but it has since been reduced and restricted to several discrete herd units (Wehausen and Hansen 1988).

The wild sheep in California have been protected from hunting since 1878, but in the late 1980s an effort to enhance their conservation through game species legislation allowed for a small number of rams to be taken from a separate subspecies population in two southern counties of the Mojave Desert (Wehausen et al. 1987). Livestock grazing and feral burros have been widespread in the Sierra Nevada landscape since 1861 (Ibid). Even though the population was protected from hunting, Wehausen et al (1987) noted that the factors causing the population decline were not addressed for many decades. Re-introduction efforts however were successful in the 1970s and 1980s and established 8 new populations throughout California, as well as expanded and augmented two others (Ibid). Mountain lion predation has severely affected the reintroduction efforts of bighorn sheep, and until recently, their presence has possibly excluded sheep from using their historical low-elevation habitat (Wehausen 1996, Elam 2008), although this remains highly debateable (Tom Stephenson, pers.comm.). Between 1907 and 1963, the mountain lion population was reduced by 12,000 individuals across California due to a bounty administered by the California Department of Fish and Game (Sitton, Sitton and Weaver 1978), and since 1972, the mountain lion population has not been hunted (Torres et al. 1996).

To expand the context of bighorn sheep in the Sierra Nevada, their habitat use is largely dictated by seasonal availability of food resources and general resource requirements. The diet of bighorn sheep is reliant on grasses and is supplemented with shrubs and woody vegetation (Wehausen and Hansen 1988). The seasonality of their diet introduces fluctuations in nutritional gain throughout the year, and is dependent on larger factors such as precipitation, elevation, and soil characteristics of the local herd's habitat (Wehausen and Hansen 1988). Bighorn sheep have been observed to avoid areas of low visibility, including conifer stands with dense understory, shrub meadows, and many riparian areas (Risenhoover and Bailey 1980, Brundige and McCabe 1986, Smith, Flinders and Winn 1991). Access to escape terrain is also important to sheep especially for ewes and lambs during the summer time months when they spend most of their time on high alpine, rocky, steep slopes (Gionfriddo and Krausman 1986, Elam 2008). Therefore, vegetation cover is an important aspect of primary sheep habitat.

2.3 Historical Landscape

The Sierra Nevada were formed 130 million years ago when the continental plates collided and caused hot rock to mold up through the ocean surface and beyond, and in later times, volcanic lava, glaciers, and earthquakes sculpted the grand peaks of today (Hill 1975). The Holocene period of the last 12,000 years has brought about de-glaciation and major climate-induced changes of the landscape (Miller and Wigand 1994).

The historical vegetation record has been constructed using various artifacts of the past: tree rings, fluvial morphology (Miller et al. 2001), ice cores (Tausch, Wigand and Burkhardt

1993), charcoal sediments (Bedwell 1973), and ancient packrat middens (Mehringer and Wigand 1987, Miller and Wigand 1994). Settlement of the Sierra Nevada by Anglo-Americans in the mid 1800s introduced livestock grazing (Burwell 1999). Before this time, tree ring evidence suggested that the landscape was dominated by shrubs, and that grass was primarily abundant around stream floodplains (Burwell 1999). Miller and Rose (1999) suggested that the old woodlands more closely resembled savanna as opposed to forests. The after-math of grazing on the landscape has potentially resulted in an opportunity for shrubs and trees to take root without vigorous competition and competitive exclusion of meadow grasses and forbs (Burwell 1999). The number of cattle, sheep and goats in the Mountains reached their peak in 1910 at almost 200,000 animals, and the extent of piñon-pine (*Pinus monophylla*), hereafter piñon, growth in the lower montane reached its peak in 1930 (Burwell 1999). There is some controversy regarding the mechanism of landscape change in the recent 150 years, however. In common literature, fire suppression on behalf of the federal and California-state department represents the proverbial black sheep of anthropogenic impact, although Miller and Wigand (1994) suggest that it did not have a major influence in the landscape until after World War II. Timber production, cattle and sheep grazing continued post World War II (Vankat and Major 1978).

The historical landscape has also been affected by fire disturbance, but it remains slightly contentious and uncertain as to what the historical fire trend was. The historical fire regime has been reconstructed from fire scars and tree rings (Swetnam and Baisan 2003), as well as radiocarbon signatures taken from sediment cores (Bedwell 1973, Miller and Tausch 2000). However, Romme et al (2009)and Baker and Shinneman (2004) have raised skepticism of past research that has suggested a high fire frequency (<25 years) predominated by low-severity fires. Fire is influenced by local and wide scale factors, and inferring landscape-wide trends with limited evidence has complicated the cross-validation with other sources (Baker and Shinneman 2004).

The mechanism of change in the Sierra Nevada landscape may be locally dependent on several factors, but in-fill of the savanna-like piñon-juniper forest of western North America has been widely documented (Romme et al. 2009).

2.4 Habitat Encroachment

The growth rate of piñon is 2.5 cm/year and only in favourable nursery settings (Barton 1993), but once established, it may live past 600 years (Tausch, West and Nabi 1981, Waichler, Miller and Doescher 2001, Gray et al. 2006). Curl-leaf mountain mahogany (*Cercocarpus ledifolius*) also grows as a common dominant shrub and tree on the east slopes of the Sierra Nevada, and has found to reach ages >130 years (Brotherson, Davis and Greenwood 1980).

Shrub and tree encroachment in the Sierra Nevada may have reduced open grasslands in the recent century, and the suggested causes are many: historical Native American burning practices, climate trends, livestock grazing or the removal thereof, rising atmospheric carbon dioxide, and fire suppression (Miller and Rose 1999). Natural succession has also been observed to explain the slow progression of increased vegetation (Baker and Shinneman 2004).

The piñon-juniper woodlands have been the focal ecosystem in many habitat encroachment studies based in the western mountains of the United States. Bighorn sheep spend the majority of their time between winter habitat – low elevation, sage, bitterbrush, and bunchgrass shrub on the edges of the piñon belt – and summer habitat – high elevation, rocky steep and grassy slopes (Elam 2008) – and therefore do not commonly utilize mid-elevations. Historical photographs of juniper stands at mid-elevations in Sequoia National Park revealed that the juniper woodlands had not changed, but the recovery of shrubs was evident since the removal of grazing livestock (Vankat and Major 1978). The consensus by Romme et al (2009) found that woodlands were favourable for growth (in-filling), and wooded shrublands were favourable when the climate is moist and without disturbance. Burwell (1999) found that tree growth and recruitment were higher in dry xeric habitat when spring and summer precipitation increased. Gray et al (2006) also found that piñon increased over decades of higher precipitation. Burwell (1999) hypothesized that encroachment in mesic habitat was a result of grazing intensity and reduced competition by forbs and grasses. Overall, the lower montane treeline occurring between 2000-2800 meters has become denser and has expanded down-slope (Burwell 1999).

3.0 Chapter 3: Methodology

3.1 Study Area

The landscape structure of the Sierra Nevada has been shaped by flowing glaciers and deep rivers, and the mountain peaks now reach as high as 4,400 meters (Storer and Usinger 1963). The valleys are abundant with deciduous and riparian vegetation, and these ecosystems transition to patchy woodlands and savanna to end at alpine meadows and rock outcrops at the highest elevations. The climate regime of the mountains in western North American has influenced fire disturbance trends as well as regular weather patterns (Miller and Tausch 2000). Human use of the landscape in the last 100 years has ranged from livestock grazing to game hunting to national park protection. Management focus has also had a dynamic trend throughout the decades, including legislated bounty permits on cougars (Holl, Bleich and Torres 2004, 65 FR 20) and active fire suppression (Miller and Wigand 1994, Burwell 1999).

The focal study area includes four of the herd units in the Sierra Nevada that have been identified as priorities for recovery (Figure 1). The Mt. Gibbs and Mt. Warren herd units are in the northern extent of the bighorn sheep range, and the Mt. Williamson and Mt. Langley herd units are in the southern region. The elevation ranges for the northern region are approximately 2100 to 3600 meters, and 1200 to 3400 for the southern region. Refer to section 2.0 for the details of vegetation.

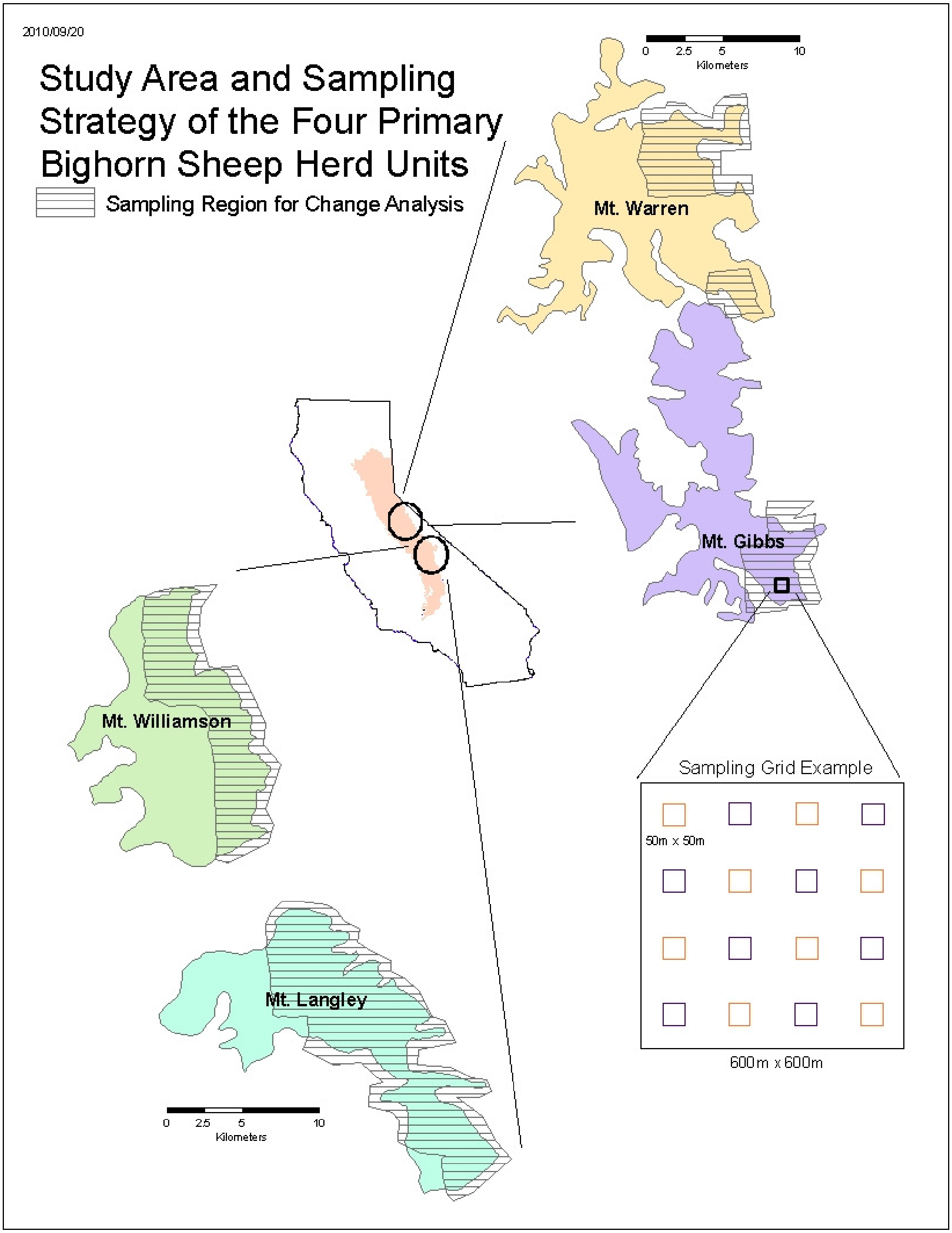

Figure 1. The sampling strategy of the herd units has adopted a randomly stratified sampling design. Eight 2500-m^2 plots were sampled for each 0.36-km^2 grid. A total of 578 plots were sampled across 71 grids throughout the four herd units

3.2 Data

Historical aerial photographs of the study area were found in hard-copy archives with partial coverage of the herd units. The historical imagery for the Mt. Warren and Mt. Gibbs herds was from 1929, and 1944 for the Mt. Williamson and Mt. Langley herds. The imagery was scanned, orthorectified, and made available by the SNBSRP and Mike Dodd. True-colour and colour-infrared aerial photographs from 2005 with 1-meter spatial resolution were collected as digital orthophoto quadrangles from the online Cal-Atlas database (http://atlas.ca.gov/). A 10-meter digital elevation model (DEM) and shape files of the herd units were also provided by the SNBSP.

3.3 Study Design

Due to major mis-registration errors between the orthorectified historical and 2005 imagery, as well as inconsistent image quality, a manual interpretation of the imagery was performed using a multi-stage sampling design. Semivariogram analysis identified 560 meters as the range for spatial autocorrelation performed on a classified tree layer from 2005 using a random sample of 300 points. Therefore the study area for each herd unit was stratified to 600 meter by 600 meter (0.36-km^2) grids in order to represent the heterogeneity of the landscape in terms of forest cover. Further sub-sampling involved subjectively choosing 50-meter plots as a practical sub-plot size based on the literature, and eight plots from each 600-meter grid were systematically sampled (Hudak and Wessman 1998, Eckhardt et al. 2000, Bowman et al. 2001, Fensham and Fairfax 2003, Manier et al. 2005, Brook and Bowman 2006, Salehi et al. 2008, Platt and Schoennagel 2009). The interpretation of the plots was performed under a given time constraint, and the sampling design also allowed for discretion in choosing alternate plots based on major distortions or shadows (Figure 1). In these cases, the closest available plot was interpreted based on priority in a clockwise direction. The DEM was resampled to 50 meters using nearest neighbour, and slope, aspect, and elevation were recorded at each plot after resampling.

Initially the 2005 colour-infrared imagery was classified in an object-based software, Definiens Developer 7.0, which was robust in identifying vegetation of interest. However, manual adjustments of the software classification were often required to ensure an accurate classification. Using the current orthorectified imagery as the reference, historical photographs were lined-up according to matched landscape features (Figure 2). As well, the raw historical photographs were used for reference because of the distortions resulting from orthorectification. In order to avoid misregistration errors of the change detection analysis, geographic information software (GIS) was used to perform the manual delineation. The result of the delineation was a historical tree cover layer that was directly comparable to the tree cover layer of current imagery. The change was calculated as a difference of vegetation cover between the historical and current dataset by area (m^2). Overall, 71- 600-meter grids were identified in the four study area units resulting in 578 50-meter interpreted plots.

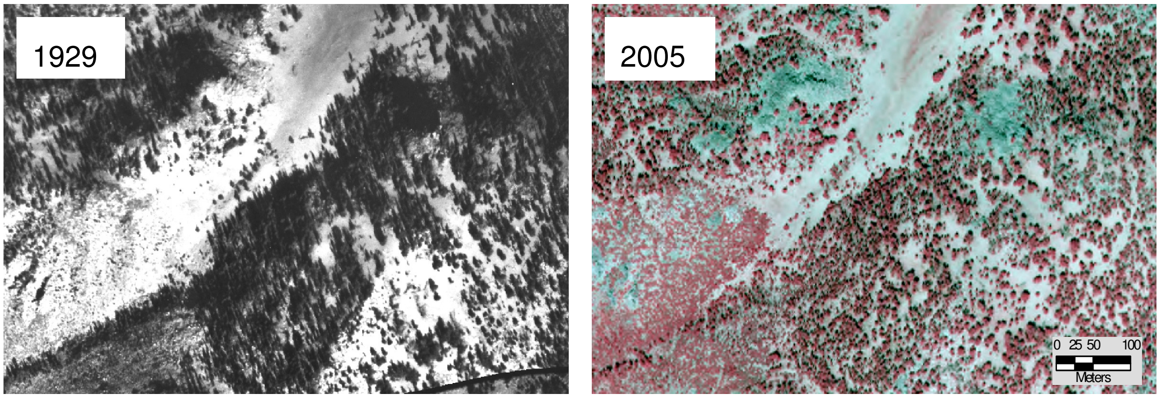

Figure 2. A small subset of the Mt. Warren herd unit showing the same landscape over 75 years.

3.4 Vegetation Classes and Interpretation Constraints

The objective of the interpretation was to identify “treed” and “non-treed” areas in each of the two datasets. With respect to bighorn sheep habitat requirements, large shrubs were considered part of the tree class. Trees and shrubs were found to have distinct shapes in the imagery, and the manual interpretation of the photographs allowed for texture, shadow, location, and surrounding vegetation to distinguish between large and small shrubs. Validation for the discernment between shrubs and trees has potential with the use of a stereoscope to measure absolute heights. Digital stereo-software was explored as a means of validation; however, the technique proved inadequate and may have been related to issues with the quality of historical imagery or scanning procedures.

The greatest challenge found for interpreting the historical and 2005 aerial photographs resulted from the difference in the appearance of a tree object between individual datasets. Tree objects in the historical imagery typically had long linear shadow casts due likely to low-angle illumination conditions, whereas the tree objects from the current aerial imagery had less pronounced and rounded shadows. The problem arose when vegetation became denser and the boundaries of tree and shrub objects were not well-defined. As well, this study has aimed to address in-filling and encroachment of trees and shrubs, and care was taken to not include canopy growth as change. The most difficult situation was identifying the size of a shrub in historical imagery, and if it had grown to a larger size in the current imagery that would negatively affect bighorn sheep. These issues have been somewhat circumvented by erring on the conservative side and defaulting to no-change during the interpretation, and the few occasions that resulted in uncertainty were assumed to have a negligible impact on the trend of overall change. The sampling design has overcome many of the constraints of interpreting historical imagery, but without ground-observation data, the validation of the interpretation was limited to the interpretation of a secondary analyst.

3.5 Validation Assessment

The confusion matrix is the standard validation assessment for post-classification analysis (Lu and Weng 2007), but there is a lack of a standard in the literature in performing an accuracy or validation assessment on specifically areas of change (Liu and Zhou 2004). For this study it was important to validate the change result, and therefore an accuracy assessment was performed by a second interpreter who explicitly identified and delineated change areas in 24 randomly assigned 50-meter plots. The change was recorded in square meters, as well as by categorical response of “change” and “no change.” The results were compared using the root mean square error (RMSE), significance and correlation tests, as well as a confusion matrix reducing the continuous change variable to “change” and “no change.” The assumption of the validation assessment was that change areas delineated by the second interpreter represented the “truth” of vegetation change.

3.6 Statistical Analysis

Based on previous literature applicable to the Sierra Nevada (Burwell 1999, Miller and Rose 1999, Gruell 2001, Romme et al. 2009), slope, aspect, and elevation were considered representative terrain variables in vegetation-cover change. As well, the additional variables of tree cover from 2005 (referred to as "2005M") and latitude resulted in five explanatory variables in a linear mixed model regression analyses in R (R Development Core Team, 2009). The units for each of the variables are included in table 3. Latitude was a categorical variable describing the Mt. Warren and Mt. Gibbs herd units as "north" and Mt. Williamson and Mt. Langley as "south".

Table 3: The units for the explanatory and response variables modeled in the regression analysis.

Variable	Units
Elevation	Meters
Slope	Percent (rise/run)
Aspect	Degrees
Tree 2005	Square meters
Latitude	"North" or "South"
Response: CHANGE	Square meters
Response: CHANGE	"Change" or "No change"

Exploratory analysis of the variables indicated that the greatest variation in the sampling design came from the eight 50-meter plots overlying the 600-meter grid (Variance Components Analysis: 77.4%). The Mt. Gibbs herd unit had the greatest amount of positive change by amount (+2.7%) and frequency, and the Mt. Langley herd unit had the least (+0.6%)(Table 4, Figure 3). The Mt. Williamson and Mt. Warren herd units were not significantly different as indicated in an analysis of variance test. The Mt. Williamson herd unit has had the greatest loss of vegetation since 1944, but overall the average change per herd unit was less than 3% (Table 5).

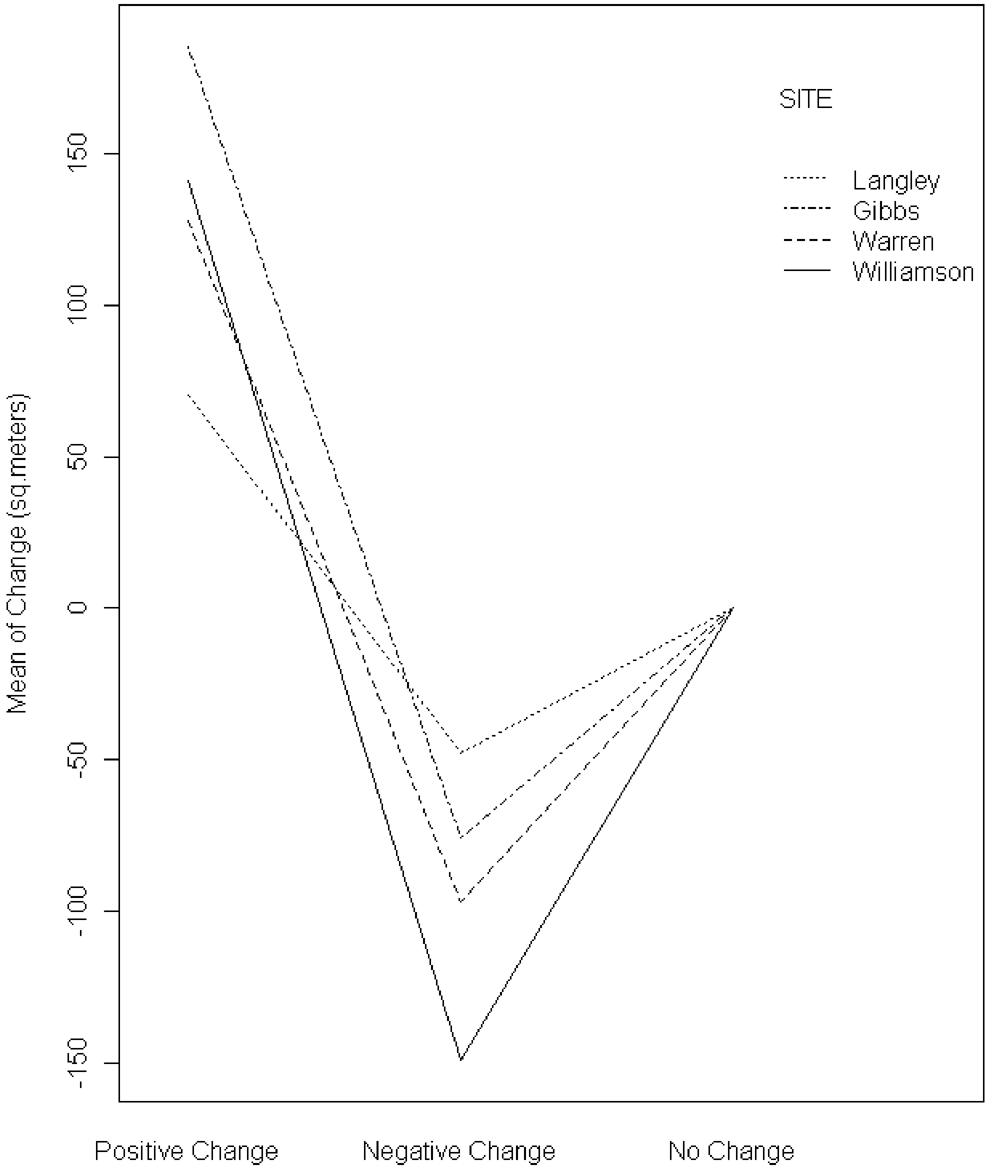

Figure 3. The means of positive and negative change by herd unit per 2500-m^2 plot. Positive change has resulted in tree and shrub growth, whereas negative change has been a loss of large vegetation.

Table 4: Frequency of change to no-change grid cells.

SITE	Grids with Change	Grids with No Change	Ratio of Change:NoChange
Mt. Gibbs	49	79	0.62
Mt. Warren	56	100	0.56
Mt. Williamson	51	93	0.55
Mt. Langley	45	105	0.43

Table 5: Summary statistics of change (m^2) by herd unit.

SITE	Minimum	Median	Mean	Maximum	Minimum Change per $2500m^2$ Plot	Avg Change per $2500m^2$ Plot	Maximum Change per $2500m^2$ Plot
Mt. Gibbs	-205.8	0	66.86	1631.10	-8.2%	+2.7%	+65.2%
Mt. Warren	-269.0	0	39.73	1150.00	-10.8%	+1.5%	+46.0%
Mt. Williamson	-705.5	0	42.72	1146.00	-28.2%	+1.7%	+45.8%
Mt. Langley	-316.6	0	15.71	571.60	-12.7%	+0.6%	+22.9%

Change was modeled as a continuous and binary response variable, and interaction terms were explored in each of the models. Latitude was not included in the full model due to the results of the exploratory analysis. The proposed mixed model included SITE and GRIDCODE as random effects:

CHANGE ~ SLOPE *ASPECT *ELEVATION *2005M + (1|SITE/GRIDCODE)

(Equation 1)

The model selection was based on variable significance, anova tests and AIC scores through stepwise deletion. However, the final two models for predicting continuous and binary change had different explanatory variables. Slope, 2005 tree cover, and the interaction term were the best predictors of change as a continuous response, and elevation and slope were the best predictors of change as a binary response. The explanatory power of each of these variables as indicated through exploratory analysis using generalized additive models (GAMs) and other methods were very low at 6%, and the wide variation between the herd units is indicated in Figure 4. Therefore, each herd unit was analyzed separately due to a lack of global variables for the study area. The starting models were chosen based on the relationships of the response to the explanatory variables (Table 6). GAMs also were further explored for detailed change trends based on the final models for each herd unit.

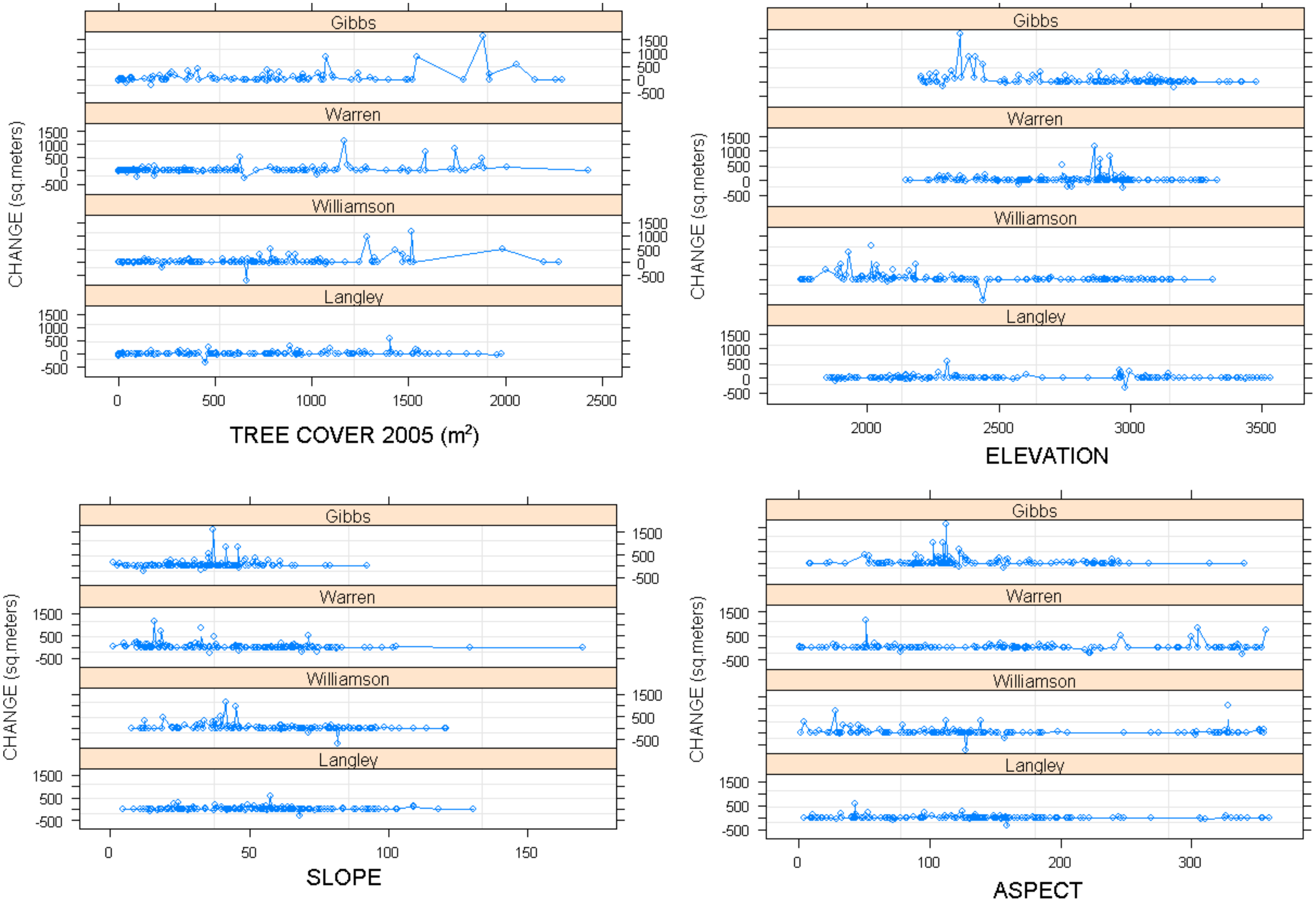

Figure 4. Trends of change for each herd unit indicated by explanatory variables.

Table 6: Starting linear mixed models for each herd unit based on exploratory analysis. The asterisks indicate interaction terms. GRIDCODE is the random effect.

Herd Unit	Starting Model
Mt. Gibbs	CHANGE ~ SLOPE *ELEVATION*2005M + (1|GRIDCODE)
Mt. Warren	CHANGE ~ SLOPE * 2005M + (1|GRIDCODE)
Mt. Williamson	CHANGE ~ ELEVATION * 2005M + (1|GRIDCODE)
Mt. Langley	CHANGE ~ SLOPE *ASPECT *ELEVATION *2005M + (1|GRIDCODE)

4.0 Chapter 4: Results

4.1 Validation Assessment

The second analyst performed an accuracy assessment of change areas by independently identifying and delineating new and lost vegetation. The Pearson's correlation of the interpreted 24 grids was good at 0.67 and using a rejection criteria of $\alpha=0.05$, the distributions were not significantly different (Kolmogorov-Smirnov test, D=0.2083, p-value=0.6749) and the variances were not significantly different (Fisher test, F=0.5738, df=23, p-value=0.1905). A significant difference between the two means, however, was found (Wilcox test, V=108, p-value=0.0411). The RMSE between the two analysts was 234.8-m^2.

Table 7: Confusion matrix of accuracy assessment on change and no-change areas.

		Interpreter #2			
		Change	No change	TOTAL	USER'S ACCURACY
Main Interpreter #1	Change	10	4	14	71.4%
	No change	0	10	10	100%
	TOTAL	10	14	24	
	PRODUCER'S ACCURACY	100%	71.4%		

*Overall accuracy: 83.3%; Kappa Index of Agreement (KIA): 67.6%.

The accuracy of detecting "change" and "no-change" areas was greater than 80% (Table 7), and therefore it is assumed that the trends of change will be indicated if present through regression analysis of the explanatory variables. The high RMSE and the difference of means between the two interpreters have resulted in less confidence in the continuous change model prediction. The continuous change models, however, will still be explored because the trends are assumed to be accurate based on the similar distribution and variance results of the two interpreters.

4.2 Regression Analysis

4.2.1 Mt. Gibbs Herd Unit

The best models for predicting change as a continuous and binary response variable included tree cover and elevation as the explanatory variables (Table 8). However, tree cover was not part of the binary change model where elevation had a negative relationship to change and was the only significant variable. Low elevations and high tree coverage are related to continuous change, and a negative interaction effect is also observed. The interaction term was further observed by plotting a conditional plot of tree cover on elevation (Figure 5). This shows that when tree cover is high, elevation and tree cover have a negative relationship, and that change is more prominent when tree cover is high and elevations are low. It is interesting to note that elevation overall has a small positive relationship to change in the model summary. A GAM was modeled with non-parametric smoothers to infer the trend of change as predicted in the binomial model by elevation (Figure 6), and change was observed to be highest at the south-east fringes of the herd unit (Figure 7).

Table 8: The best models for predicting change in the Mt. Gibbs herd unit. Asterisks indicate significance.

Response	Explanatory Variables	β-Estimate	Std. Error	t-value/ z-value	Significance
Change Continuous (m^2)	(Intercept)	6.638×10^{1}	2.0085×10^{2}	0.318	
	Elevation	1.385×10^{2}	7.273×10^{-2}	-0.191	
	Tree Cover 2005	9.724×10^{-1}	2.432×10^{-1}	3.998	*
	Elevation:Tree Cover	-3.245×10^{-4}	9.062×10^{-5}	-3.581	*
Change Binary (change=1)	(Intercept)	4.139	2.078	1.991	0.0465*
	Elevation	-1.551×10^{-3}	7.266×10^{-4}	-2.135	0.0328*

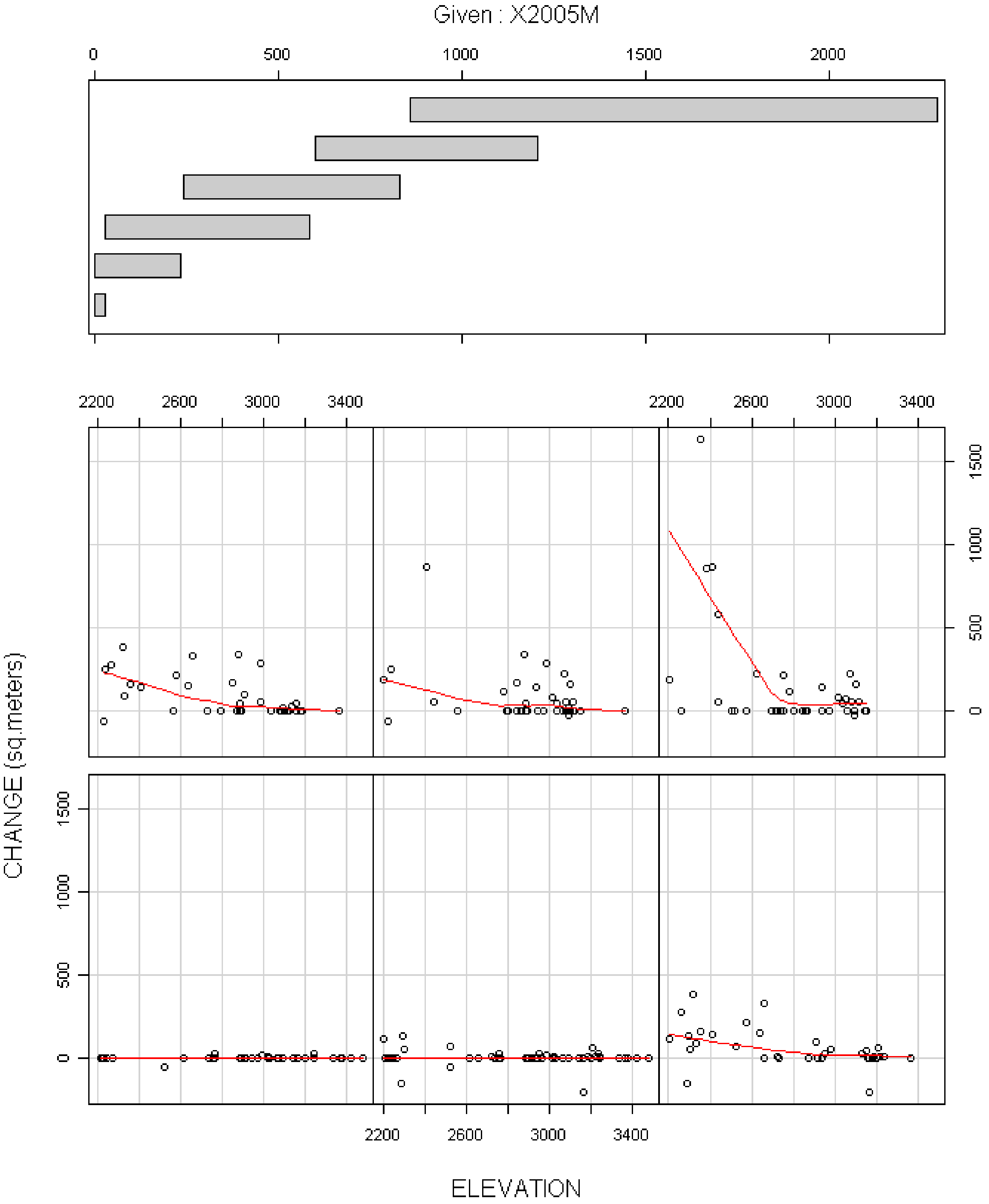

Figure 5. The interaction of elevation and tree cover for the Mt. Gibbs herd unit indicated by the continuous response model. The trend lines indicated in red show a sharp change in the relationship of elevation to tree cover when tree cover exceeds 900-m^2 (shown at the top of the bar chart, and the top-right graph).

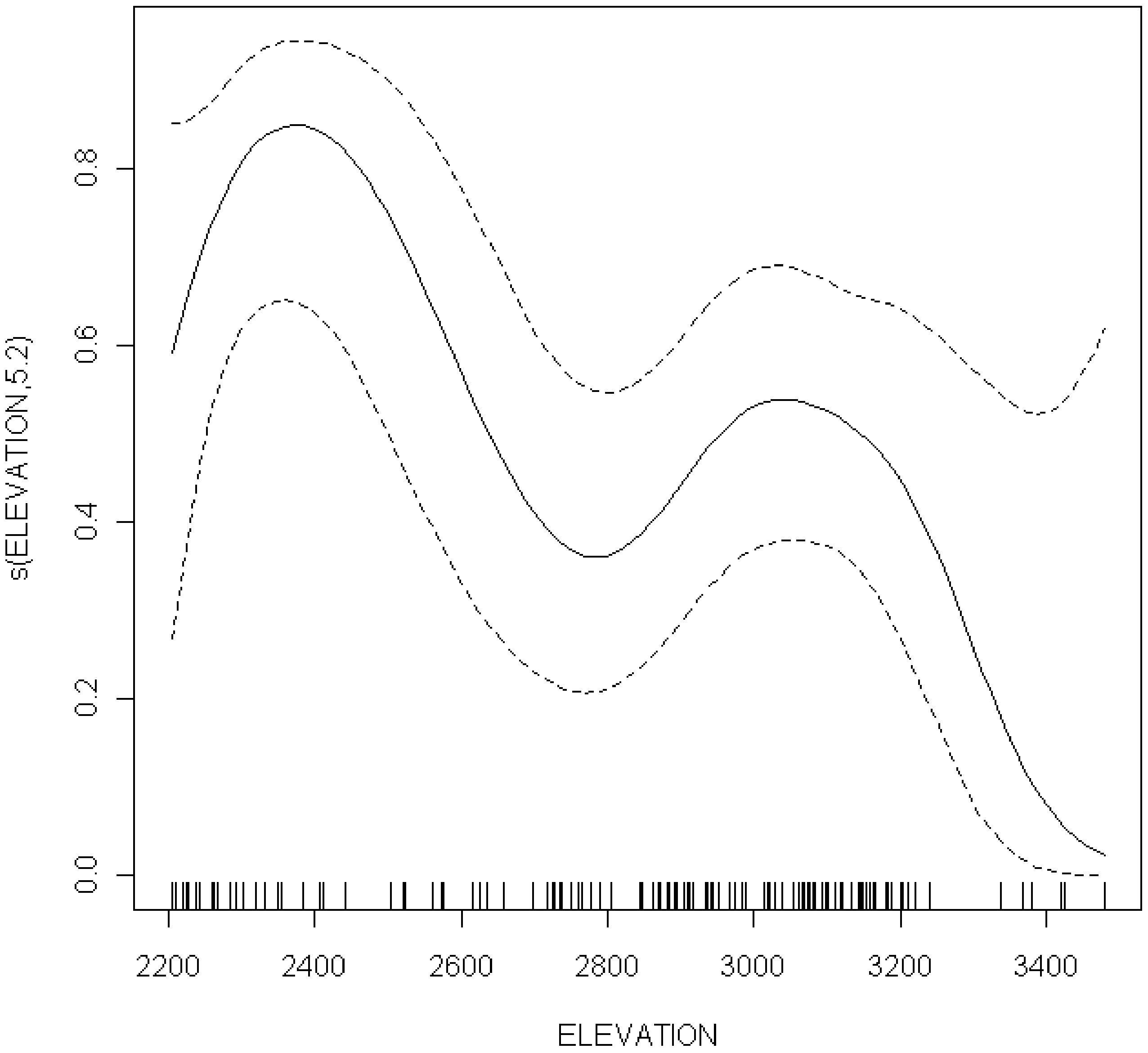

Figure 6. The change trend in the Mt. Gibbs herd unit. 95% CI indicate that change is occurring at elevations between 2275-2500 meters. The y-axis is labeled with the degrees of freedom used for the smoothed trend line but occurs on the scale of the change response (1=change, 0=no change). The tick marks at the bottom indicate the sampling distribution of the variable.

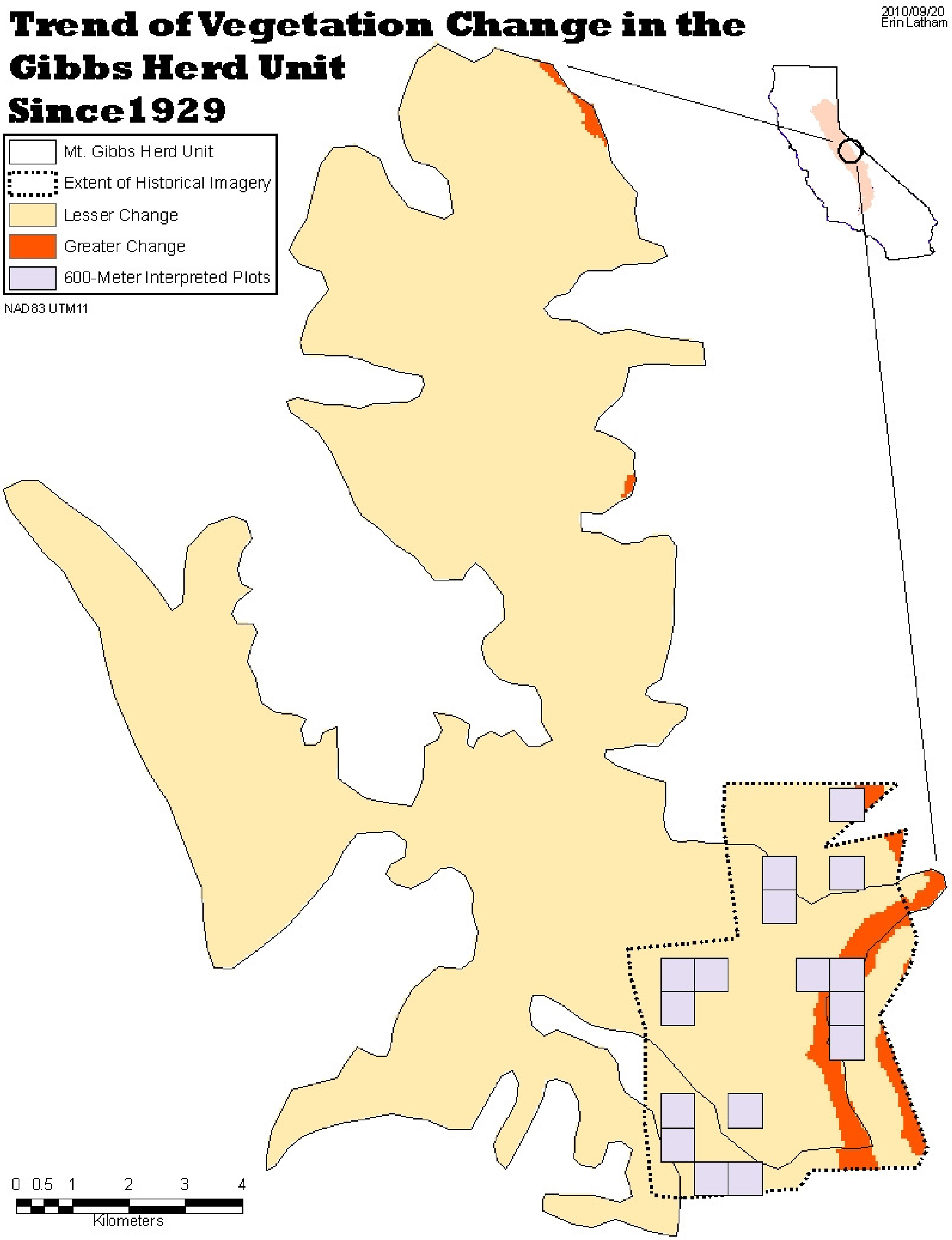

Figure 7. Change in the Mt. Gibbs herd unit as modeled by a generalized additive model as a binary response of change and no-change.

4.2.2 Mt. Warren Herd Unit

Both slope and tree cover (2005M) were consistent predictors of continuous and binary change (Table 9). However, slope was not significant in the continuous change model. A plot of slope and tree cover modeled as a GAM has indicated with 95% confidence that slopes of <47% are associated with change, and tree cover <200-m^2 is not associated with change (Figure 7). The confidence of prediction for tree cover was not as high as observed by the wide confidence intervals.

Table 9: Tree cover and slope were the explanatory variables in the best model for continuous change (m2) and binary change.

Response	Explanatory Variables	B-Estimate	Std. Error	t-value/ z-value	Significance
Change Continuous (m^2)	(Intercept)	23.61523	28.32397	0.834	
	Slope	-0.65426	0.42667	-1.533	
	Tree Cover 2005	0.07933	0.02070	3.832	*
Change Binary (change=1)	(Intercept)	-0.0739767	0.4905115	-0.151	0.8801
	Slope	-0.0150842	0.0076505	-1.972	0.0486*
	Tree Cover 2005	0.0007127	0.0003469	2.054	0.0399*

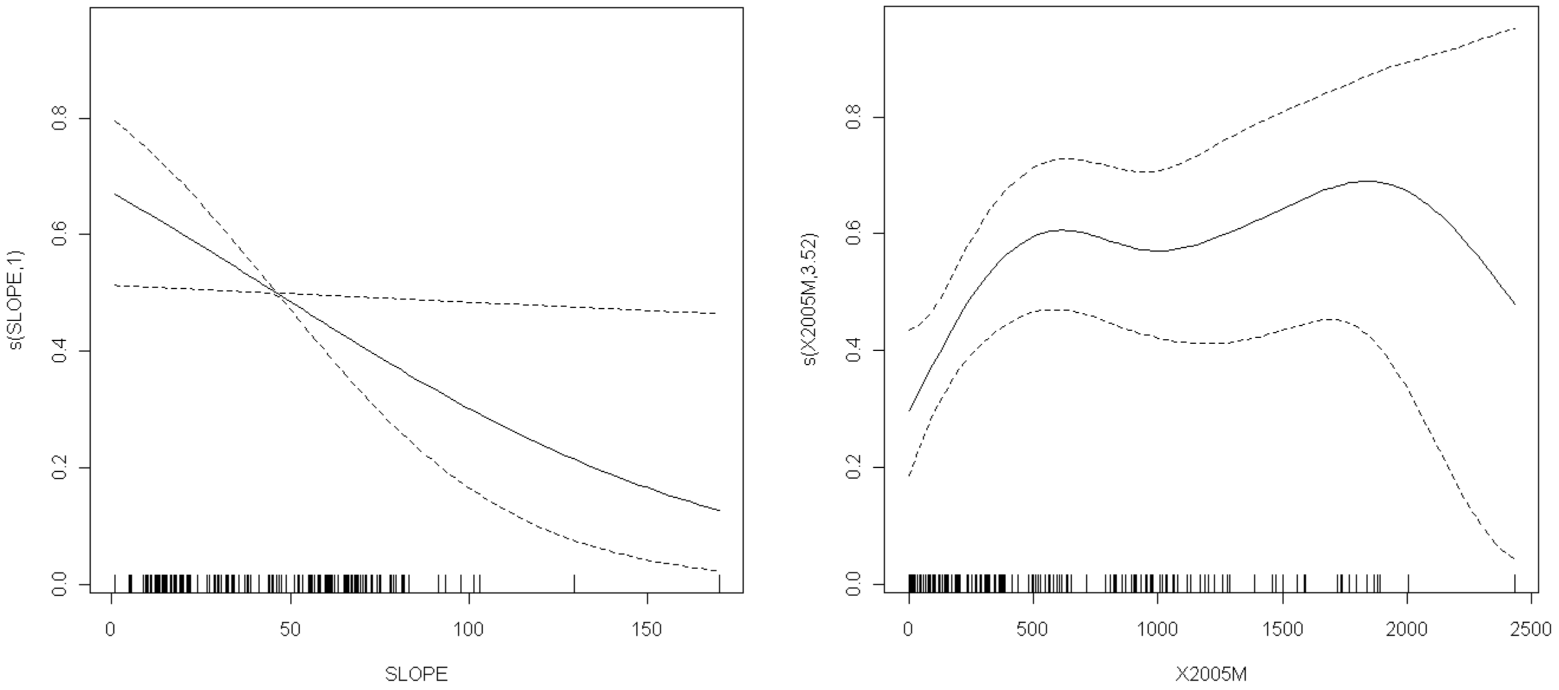

Figure 8. The trends of slope and 2005 tree coverage (X2005M) modeled as a generalized additive model. The dashed-lines indicate two standard-errors or approximately 95% confidence of the prediction, and the crossed confidence intervals in the slope figure indicate a linear trend. The y-axis is labeled with the degrees of freedom used for the smoothed trend line but occurs on the scale of the change response (1=change, 0=no change). The tick marks at the bottom indicate the sampling distribution of the variable.

4.2.3 Mt. Williamson Herd Unit

Similar to the Mt. Gibbs herd unit, elevation, tree cover and the interaction term were the best explanatory variables of continuous change in the Williams herd unit with only tree cover and the interaction term as significant (Table 10). Elevation was the only significant predictor of the binomial model, and a GAM was used to predict the trend of change for the herd unit (Figure 10). Change was observed to be more dramatic in a narrow elevation margin occurring on the south-east fringes of the herd unit from approximately 1950-2300 meters.

Table 10: The best models for change in the Mt. Williamson herd unit included elevation, tree cover, and the interaction term as significant.

Response	Explanatory Variables	B-Estimate	Std. Error	t-value/ z-value	Significance
Change Continuous (m^2)	(Intercept)	-1.998×10^{1}	1.284×10^{2}	-0.156	
	Elevation	4.991×10^{-3}	5.125×10^{-2}	0.097	
	Tree Cover 2005	5.281×10^{1}	0.1660	3.182	*
	Elevation:Tree Cover	-1.903×10^{-4}	7.357×10^{-5}	-2.587	*
Change Binary (change=1)	(Intercept)	4.626	1.699	2.723	0.00647*
	Elevation	-2.123×10^{-3}	6.966×10^{-4}	-3.047	0.00231*

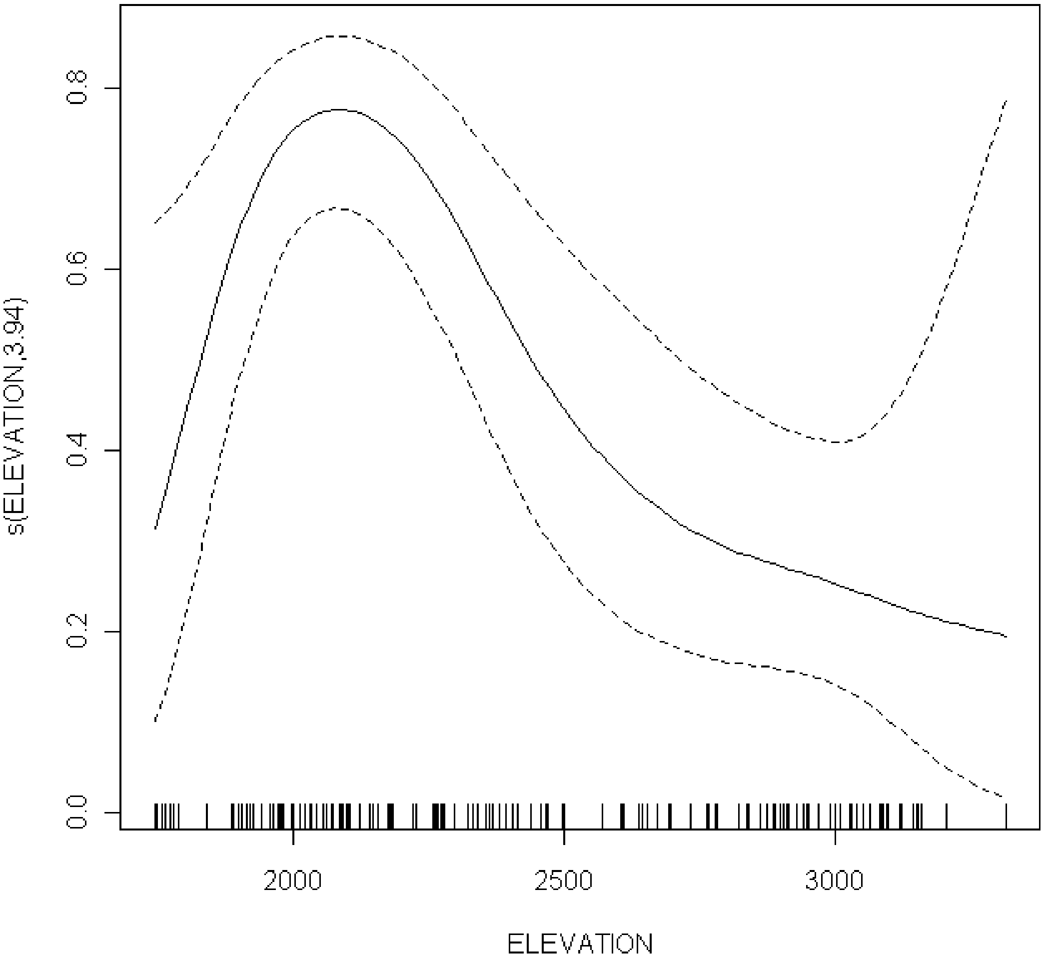

Figure 9. The trend of change by elevation in the Mt. Williamson herd unit. The 95% CI indicate the change is occurring between 1950-2300 meters. The y-axis is labeled with the degrees of freedom used for the smoothed trend line but occurs on the scale of the change response (1=change, 0=no change). The tick marks at the bottom indicate the sampling distribution of the variable.

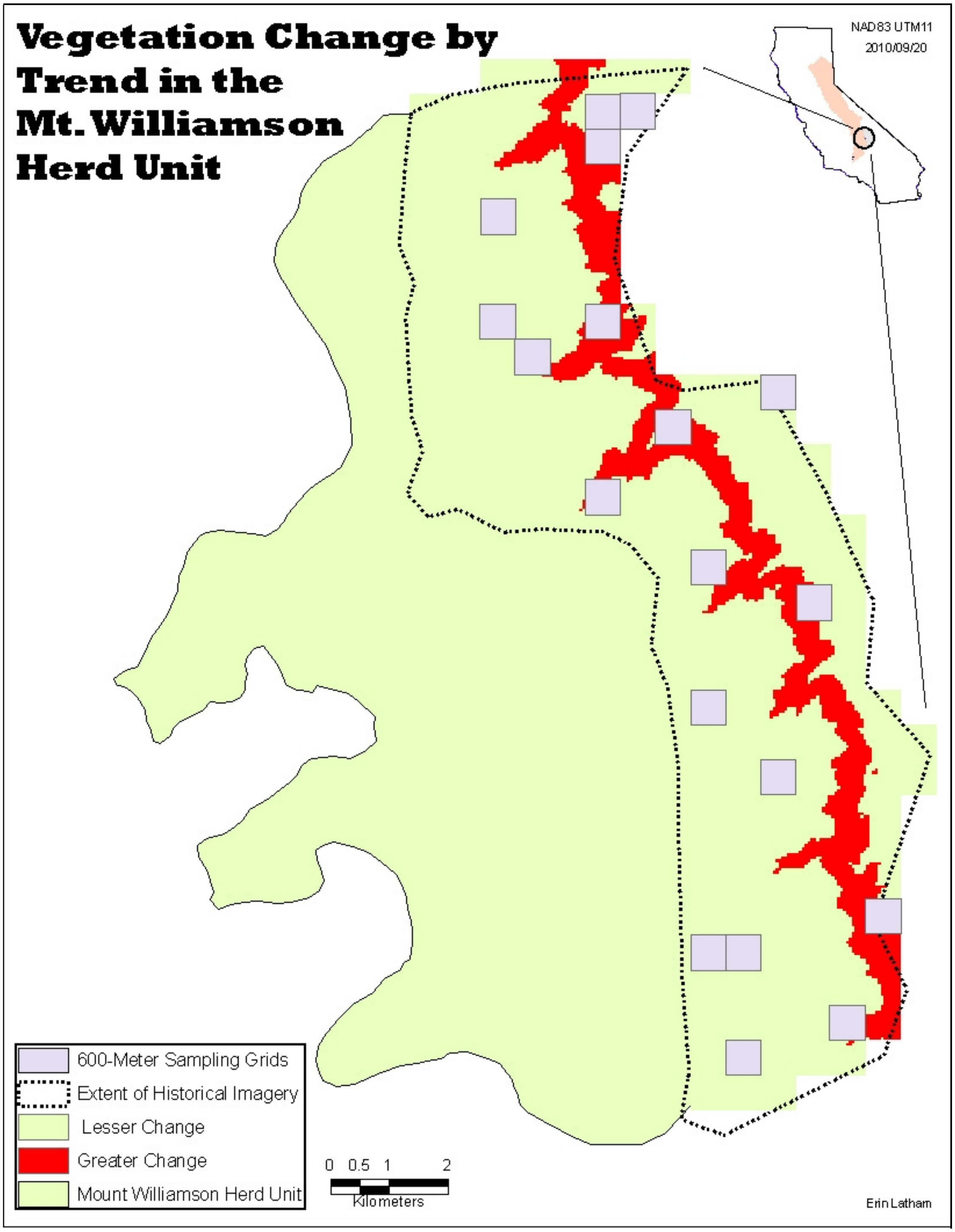

Figure 10. Change observed in the Mt. Williamson herd unit as modeled by a generalized additive model as a binary response of change and no-change.

4.2.4 Mt. Langley Herd Unit

Tree cover was the only significant predictor to continuous change for the Mt. Langley herd unit, although aspect was also shown to have some explanatory power (Table 11). There were no significant predictors in the Mt. Langley herd unit when change was modeled as a binary response.

Table 11: The explanatory variables for predicting continuous change in the Mt. Langley herd unit included aspect and tree cover. The intercept was the only significant component in the Mt. Langley model.

Response	Explanatory Variables	B-Estimate	Std. Error	T-value/ z-value	Significance
Change Continuous (m^2)	(Intercept)	16.4242	12.7687	1.286	
	Aspect	-0.1233	0.0655	-1.882	
	Tree Cover 2005	0.0250	0.0107	2.325	*
Change Binary (change=1)	(Intercept)	-0.4270	0.1956	-2.183	0.0290*

5.0 Chapter 5: Discussion

Change was concentrated at low elevations and on the south-east fringes of the Mt. Gibbs and Mt. Williamson herd units. The low elevations were associated with change in Mt. Gibbs and Mt. Williamson were unique to the sampling area of the historical imagery, and therefore inferring the same trend to the remainder of the Mt. Gibbs and Mt. Williamson herd units cannot be done with confidence. Vegetation change may be occurring at higher elevations, but the trend may also have been obscured by the dominant influence of change at the lowest elevations. The eastern front range of the Sierra Nevada borders areas of increased development and human-use relative to the higher-elevation core areas found within many of the herd units. Habitat edges are notoriously vulnerable to disturbance (Swenson and Franklin 2000), and bighorn sheep are known to be vulnerable to human recreational disturbance (Papouchis, Singer and Sloan 2001). Increased tree encroachment and vegetation change would increase the susceptibility of bighorn sheep at low elevations during the winter season, the most vulnerable time of the year (Wehausen and Hansen 1988). Because of the potential anthropogenic factor, further investigation may be required to test the sensitivity of the habitat and tree encroachment to recreational activity in and surrounding the bighorn sheep herd units.

Vegetation change has been shown to have significant variation between and within the herd units. The previous literature has identified the correlation of change with xeric or mesic habitat attributes which are structurally identified using a combination of terrain and field measurements (Burwell 1999). Other studies, however, have used proxy variables such as aspect and slope to infer moist or xeric conditions (Mast et al. 1997, Manier et al. 2005, Weisberg et al. 2007, Platt and Schoennagel 2009). Aspect was hypothesized to be associated with increased encroachment, but the relationship was not observed in this study and therefore the hypothesis was rejected. The 2500-m^2 plots may not have been at the appropriate scale to associate increased vegetation with moist conditions using aspect as a proxy variable. As well, latitude was not observed to be highly significant, but there was a significant difference between the Mt. Gibbs and Mt. Langley subunits. Therefore, this study could not establish a relationship between northern latitudes and increased vegetation encroachment and the hypothesis has been rejected, but there is indication that we failed to detect the relationship in this analysis.

Mt. Warren was the only herd unit where change was consistently modeled by the same two explanatory variables. Information is lost when a continuous variable is reduced to a categorical variable, and modeling change as a binary response subsequently altered the relationships of the independent and dependent variables for three of the four herd units. The median of change for each of the herd units was zero, and approximatley half of the plots sampled had no change; however, the mean for each herd unit was greater than zero (15.7m^2 - 66.9m^2). This may have been a result of large changes occurring at the periphery of the sampling distribution, for instance when tree cover exceeds 1000-m^2 for the Mt. Gibbs, Mt. Warren and Mt. Williamson herd units. Therefore by reducing the response to “change” and “no-change” areas, the frequency of no-change has increased weight in trend line, and extreme change values that were potentially more sensitive to interpretation bias have been placated.

Although the recognition of change in the landscape between the interpreters was moderately accurate, the change results between the two interpreters were different, but each interpretation also utilized different methods. The first interpreter had to initially classify and manually validate the current imagery, and then manually classify the historical imagery. The second interpreter made only a single delineation of the change area, and therefore differences between the two interpreters may be attributed to the sensitivity of the delineation. Although there does appear to be sensitivity in the delineation of object boundaries, which is magnified in the results of the main interpreter, the resulting trends are still similar between the two interpreters, and therefore our assumption stated previously has not been violated. The results of the validation assessment and the change in relationships of the explanatory variables have suggested greater confidence in the trend of change when modeled as a categorical rather than a continuous response. Differences in air-photo interpretation are well-documented (Foody 2002, Powell et al. 2004), but by employing experienced interpreters and validation assessments with well-defined land-cover classes, the confidence of the classification increases.

The results of the exploratory analysis and regression modeling have indicated that tree encroachment did not have a strong relationship with the predictor variables of slope, aspect, and elevation as other studies have found (Mast et al. 1997, Manier et al. 2005, Brook and Bowman 2006, Salehi et al. 2008, Platt and Schoennagel 2009). However, many of the predictor variables were still significant in the models, and the models which are considered more reliable and less influenced by extreme values are those modeled as a binary response. Other change detection studies in the western United States that utilized historical imagery have also found increased vegetation change at low elevations (Manier et al. 2005, Weisberg et al. 2007, Platt and Schoennagel 2009) and low slopes (Weisberg et al. 2007). The lack of aspect as a significant predictor variable may be due to a relationship that was too weak given the low amount of change in all of the herd units.

The mechanism of change in the study area was not directly tested in this research, but anthropogenic disturbance is suspected to be a contributing factor. In addition to this influence, observed especially for the Mt. Gibbs herd unit, further vegetation change may be occurring by slow succession. Miller and Tausch (2001, p.17) identified that "woodland dynamics operate at long-term scale and respond to temperature, precipitation, and… fire", and perhaps the explanatory variables used in this analysis failed to encompass the vegetation change as it responds to larger climatic factors. Baker and Shinneman (2004) have also observed that slow change may appear as "invasive". The mechanism of change may only be speculated here, but it is worthy to note that the average change has been minimal and slow given the time frame (0.1-2.7%), and with an absence of strong predictor variables, it could be random and responding to suite of variables that are part of the successional regime. It may also be that the explanatory variables used in this analysis could not adequately explain the dramatic change, such as a 65% increase in tree cover, observed in some areas. The systematic random sampling approach, therefore, may not have adequately sampled change areas in the herd units, and smaller-scale focal studies may develop better inferences on the mechanism of change.

The power of long-term monitoring may be found in numbers, and the incorporation of multiple historical images in a long-term landscape monitoring study is preferable to a single two-date change detection study. The primary difficulty of working with historical imagery is the absence of ground-observation data to validate the interpretation, but successive imagery may help to separate static from permanent objects in the landscape. As well, the increased number of datasets may enable more analysis techniques, such as principal components (PCA) or multivariate alteration detection (MAD). Many studies utilizing historical aerial imagery use three imagery dates (Schlesinger and Gramenopoulos 1996, Thomlinson et al. 1996, Mast et al. 1997, Eckhardt et al. 2000, Augustin et al. 2001, Manier et al. 2005, Brook and Bowman 2006, Thomson et al. 2007, Zomeni et al. 2008, Pringle et al. 2009), and the occasional study has used six dates, and up to 12, for change monitoring (Herwitz et al. 2000, Laliberte et al. 2004, Okeke and Karnieli 2006). Multiple sets of imagery therefore are worth more together than their individual parts, and long-term landscape monitoring would greatly benefit from several historical sources, as well as multiple current and future datasets.

6.0 Chapter 6: Conclusion

The objective of this study was to undertake a change detection analysis of the Sierra Nevada using historical aerial photographs. The analysis attempted to characterize the trend of piñon and mountain mahogany encroachment around the bighorn sheep herd units in an effort to assist managers of the Sierra Nevada Bighorn Sheep Project (SNBSRP) in restoring lost or vulnerable habitat to further aid the recovery of the subspecies.

The trend of vegetation was found to be variable in the four primary bighorn sheep herd units investigated. The largest changes observed in the herd units resulted in increases of 23-50% tree cover per 2500-m^2 plot. The frequency of no-change plots was higher, and the average change per plot was less than 3%. Overall, an average increase of tree cover was found in all of the herd units, confirming the findings of Romme et al (2009), although the change is more dramatic in some areas, and non-existent in others. The trend of tree encroachment was associated with the low elevations on the east and south-east fringes of the Mt. Gibbs and Mt. Williamson herd units, which may be associated with anthropogenic disturbance such as roads and recreational areas. Increased tree cover in the Mt. Warren herd unit was associated with low slopes and high tree cover. The change in the Mt. Langley herd unit could not be modeled with confidence due to the absence of explanatory variables when change was modeled as a binary response, as well as it had the least change of all the herd units.

Indications for the mechanism of change in the Sierra Nevada is likely attributed to anthropogenic disturbance, both historical and present, and possibly natural succession indicated by the majority of sites without change as well as the lack of explanatory power by the terrain variables typically associated in the literature with vegetation change.

This study has demonstrated a valid sampling approach for interpreting a large study area with historical aerial photographs, and demonstrates the importance of historical remote sensing data for long-term landscape monitoring. The limitations of the historical data may be overcome through a multi-stage sampling approach, experienced interpreters using well-defined land-cover classes, multiple historical datasets and sources, and validation assessments utilizing all capable hardware and software. Historical datasets should be continually recycled for new and repeat analyses in order to establish a standard monitoring framework on which to base future landscape monitoring campaigns. The standards of interpreting historical remote sensing imagery have been set, and the historical baseline state of the landscape has now been extended beyond 40 years.

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Appendix A. Final Regression Models by Herd Unit

Mt. Gibbs

CHANGE (m^2) ~ ELEVATION +2005M +ELEVATION:X2005M+ (1|GRIDCODE)

(Eq. 1)

CHANGE (0/1) ~ ELEVATION + (1|GRIDCODE)

(Eq. 2)

Mt. Warren

CHANGE (m^2) ~ SLOPE +2005M + (1|GRIDCODE)

(Eq. 3)

CHANGE (0/1) ~ SLOPE + 2005M + (1|GRIDCODE)

(Eq. 4)

Mt. Williamson

CHANGE (m^2) ~ ELEVATION +2005M +ELEVATION:X2005M+ (1|GRIDCODE)

(Eq. 5)

CHANGE (0/1) ~ ELEVATION + (1|GRIDCODE)

(Eq. 6)

Mt. Langley

CHANGE (m^2) ~ ASPECT+ X2005M +(1|GRIDCODE)

(Eq. 7)

CHANGE (0/1) ~ 1 + (1|GRIDCODE)

(Eq. 8)