Estimating Land Cover for Three *Acequia*-irrigated Valleys in New Mexico using Historical Aerial Imagery between 1935 and 2014

Robert Paul Sabie, Alexander Fernald, and Marcus Ryan Gay*

New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, NM 88003
*Corresponding Author Email: rpsabie@nmsu.edu

Abstract

Land use/land cover (LULC) datasets at a local spatial scale are important for investigating local linkages between hydrology, community, ecology, and economy in valleys in northern New Mexico irrigated by *acequias* (community-managed watercourses). However, datasets do not currently exist at the necessary spatial and temporal scales to fully investigate these linkages. These valleys are both ecologically and culturally significant to New Mexico and are experiencing change due to pressures from water demand, climate, population, and development. The purpose of this research was to create and analyze LULC datasets for three *acequia*-irrigated valleys (Alcalde, El Rito, and Arroyo Hondo) in northern New Mexico for eight points in time between 1935 and 2014. Polygons were manually digitized from georeferenced historical aerial photographs and, subsequently, classified using standard aerial photo interpretation techniques. A less common thematic accuracy assessment approach, fuzzy-set theory, was performed for each of the twenty-four LULC maps. Overall match for these maps ranged between 80.4 - 93.8 %. Agricultural land is still a dominant land cover in the three valleys; however, it is steadily declining and becoming fragmented by new roads and structures. As agricultural lands decrease, all three valleys show an increase in Non-Irrigated land. The results of this analysis corroborate and quantify the informal community accounts of LULC change and provide researchers a unique dataset for further investigating linkages between LULC, hydrology, and community-managed watercourses.

Keywords: land cover, land use, fuzzy-set accuracy, acequia, aerial photo interpretation, New Mexico

1. Introduction

The *acequia* systems of New Mexico are community-managed watercourses used for irrigation and are typically located in alluvial floodplains which overlay relatively shallow aquifers (Fernald et al. 2015). Archeological evidence suggests that irrigation practices were used in New Mexico by Native Americans prior to Spanish settlers establishing the current arrangement of managed irrigation canals over 400 years ago (Ackerly et al. 1994). Historically in New Mexico, there were up to 1,927 *acequias* that operated at different points in time (Ackerly et al. 1994) and 800 (Weston Solutions 2002) to over 1,000 (Brown and Rivera 2000) *acequias* are estimated to be active in New Mexico today. According to section 73-2-65 of the *New Mexico Statutes Annotated*, each *acequia* is managed as a local governmental agency and is considered a political subdivision.

Acequia communities in northern New Mexico, as well as mountain valley communities around the globe, face many challenges due to changes in climate, water availability, community structure, and development. To better understand these complex interactions, researchers from multiple disciplines within academia examined the relationships among communities, surface water, groundwater, economics, and ecosystem functions using a coupled natural-human system approach (e.g., Guldan et al. 2013; Turner et al. 2016; Rivera 1998; Ochoa et al. 2013; Fernald et al. 2015; Rodrâiguez 2006). Modeling the interactions of these systems necessitates the collection of an assortment of historical data, such as population, income, surface-water flow, and land use and land cover (LULC).

LULC information is frequently used as one of the parameters for understanding and modeling complex relationships between human and natural systems. Land use and land cover are often inappropriately used interchangeably so it is necessary to state the difference. Land use is generally characterized as human "activities on land which are directly related to the land" and land cover is characterized by the "vegetational and artificial constructions covering the land surface" (Anderson 1976). In the water-resource research arena, LULC is used in assessing soil moisture and evapotranspiration (Zhang and Schilling 2006), estimating potential groundwater recharge rates (Scanlon et al. 2005), assessing groundwater-surface water interactions (Saha et al. 2012), monitoring wetlands (Rebelo, Finlayson, and Nagabhatla 2009), and modeling water availability (Menzel et al. 2009).

The National Land Cover Dataset (NLCD) is often used for researching biodiversity conservation, phenology of ecosystems, land cover change, and water quality in the United States. The NLCD is produced by applying supervised classification methods to satellite imagery and is most appropriately used for assessing land cover on a regional or national scale (Homer, Fry, and Barnes 2012). Although the use of the NLCD is widely accepted, two major limitations for examining detailed historical changes at a local scale are: 1) the relatively small temporal range (1992-2011) and 2) low thematic accuracy (e.g., under 66 % overall accuracy for Level II classes for the 1992 NLCD) (Stehman et al. 2003). Low-class accuracies can lead to over or under estimating the areal extent of LULC classes. For example, the 2001 NLCD Level II class accuracies ranged between 32 and 97% (Wickham et al. 2010). Because of these limitations, it is necessary to develop a LULC dataset for the *acequia*-irrigated valleys at the local scale.

Previous research explored mapping land use in *acequia*-irrigated valleys in northern New Mexico using aerial photo interpretation techniques. Land use estimates were produced for three points in time (1962, 1997, and 2003) with six classes along a section of the Rio Grande near Alcalde, New Mexico for assessing the impacts of land use change on local water resources (Ortiz et al. 2007). The findings suggest that residential land use in this area increased 553% between 1962 and 2003. By means of a similar approach, the Rio Hondo watershed land use for five classes was mapped for 1935, 1969, and 2010 in order to investigate the factors impacting community resiliency (Miller 2013). The study found that approximately 25% of the agricultural land changed to non-agricultural land uses between 1969 and 2010. Both studies provided estimates of land use that met the goals of their respective studies, however, neither provided any assessment of the positional accuracy of the georeferenced aerial images and thematic accuracy of the land use classifications, nor set up any topology rules. Furthermore, the land use classes assigned in these two studies were slightly different. For example, Ortiz used a generalized residential land use class that included driveways, yards, structures, and non-irrigated yards, whereas Miller did not have a residential land use class and instead digitized individual structures. Because of the inconsistencies between the approaches in these studies, it would be inappropriate to use the land use analysis results for comparisons of the two valleys.

The objective of this research is to produce comparable LULC datasets for three *acequia*-irrigated valleys in northern New Mexico to support modeling of both hydrologic and socio-economic processes at a local scale. This LULC assessment adds to the current body of research on *acequia*-irrigated valleys and provides researchers with a dataset that distinguishes the subtle changes in LULC in these valleys. The information from this analysis offers historical, consistent, and accurate measures of LULC and associated change, which were previously unavailable. These datasets are beneficial to researchers, agriculturalists, policy makers, and the public interested in changes in LULC in these historic valleys.

2. Methods

2.1 Study Location

LULC analysis was performed on three *acequia*-irrigated valleys in northern New Mexico. Different water flow regimes were represented in the three study sites: low (El Rito), medium (Hondo), and high (Alcalde) (Figure 1). The climates of each site are typical of semi-arid steppe (BSk), where annual precipitation is below the potential evapotranspiration and where there are hot and dry summers and cold winters. The majority of the precipitation occurs during the monsoon season between July and September. Streamflow derives primarily from mountain runoff of snowmelt. Agriculture is a primary activity in the valleys and typical crops include alfalfa, pasture grasses, apples, chile, corn, and other specialty crops (Fernald, Baker, and Guldan 2007).

The El Rito study valley is centered around 36.345° N, 106.186°W, with an average elevation of 2,100 m above sea level (ASL). The unincorporated community of El Rito is in the center of the valley. The 30-year average annual precipitation is 320 mm and the average minimum and maximum temperatures are 1.5°C and 18.2°C (National Climatic Data Center 2016). Water flows from the Carson National Forest to the northwestern portion of the study area and is diverted into seven *acequias* from the El Rito River.

The Hondo study valley is centered around 36.535° N, 105.614°W with an average elevation of 2,200 m ASL. The communities within the Hondo study area include Valdez and Arroyo Hondo. The community of Arroyo Seco is just outside the study area boundary and the Taos Ski Valley is approximately 12 kilometers to the northwest. The average annual precipitation is 324 mm, the average minimum temperature is -0.11°C, and the average maximum temperature is 18.1°C (National Climatic Data Center 2016). The twelve *acequias* within the Hondo study area use water diverted from the Rio Hondo that flows from the Sangre de Cristo mountain

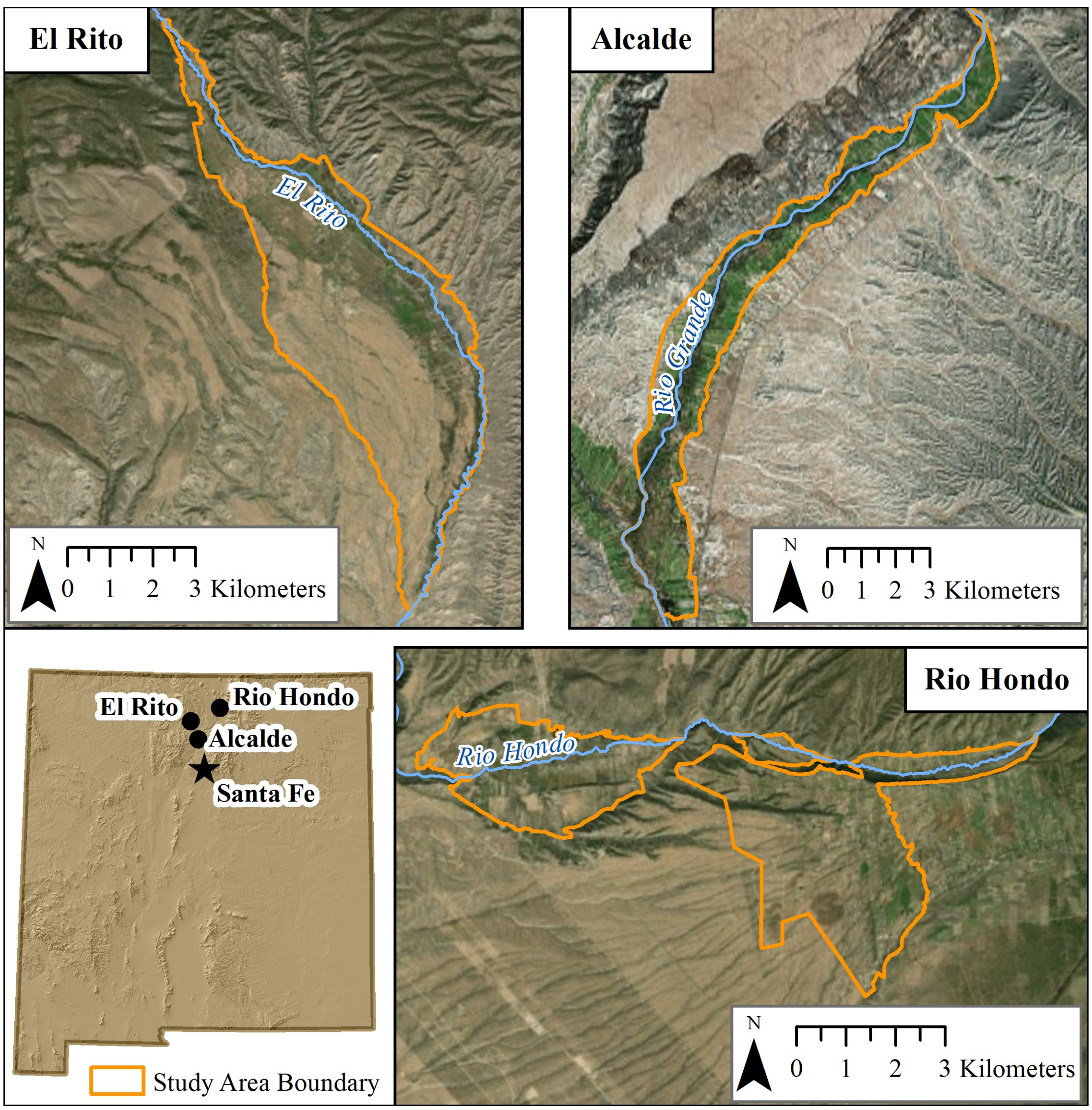


Figure 1. Location of the three *acequia*-irrigated valleys used in this study. Background imagery source: Esri and DigitalGlobe, October 2016.

range to the northeast.

The Alcalde study valley is centered at approximately 36.126°N, 106.032°W. It has an average elevation of 1,744 m and includes the communities of Velarde, La Canova, Lyden, Estaca, El Guique, and Alcalde. The Pueblo of Ohkay Owingeh and the city of Española are immediately to the south. The 30-year average annual total precipitation is 296 mm, the average minimum annual temperatures is 1.1°C, and the average maximum annual temperature is 19.4°C (National Climatic Data Center 2016). The Rio Grande flows through the center of the valley and water is diverted from the river into nine *acequias*.

2.2 Aerial Photograph Processing

Georectification was performed on 187 single aerial photographs that were obtained for the three valleys between 1935 and 2014, the earliest and most recently available imagery. The data were acquired from the USGS Earth Explorer website (http://earthexplorer.usgs.gov/) and the Earth Data Analysis Center at the University of New Mexico (Table 1). All images prior to 1997 were georeferenced in ArcGIS to 2014 National Agriculture Imagery Program (NAIP) imagery. NAIP imagery goes through orthorectification prior to being made publicly available and has a reported horizontal accuracy less than or equal to 6 meters (US Department of Agriculture 2015). Aerial photographs prior to 1997 were not downloaded as orthorectified products and thus had three types of distortion and displacements: 1) radial distortion toward the outside edges as an artifact of lens distortion; 2) radial displacement due to the roll, pitch, and yaw of the aircraft; and 3) topographic displacement due to the relief between the mountains and the irrigated valleys. A spline transformation was used with a minimum of forty control points to optimize local accuracy of the georectified aerial photographs. Both hard (e.g., building corners, road intersections) and soft (e.g., trees, shrubs) control points were selected from the reference NAIP imagery and aerial photos. Following georeferencing, the aerial photographs were subset and mosaicked to the extent of the study areas.

The imagery with the highest spatial resolution and least amount of distortion was selected in each valley for each decade going back to 1935, however, in some cases, imagery was not available or the quality was poor. Aerial photographs are not available for the Hondo site in the 1940s, thus aerial photographs from 1953 were used. Neither the 1958 nor 1959 Hondo aerial photograph mosaic covered the entire study area, thus the best photographs from those years were combined into a single image. The available aerial photographs for all three valleys in the 1980s were low quality and unusable for classification. All aerial photographs are black and white except for the 2005 and 2014 NAIP photographs.

Following georectification and mosaicking, horizontal accuracy was assessed for each aerial photo mosaic following standard Federal Geographic Data Committee methods (FGDC 1998). The 2014 NAIP imagery was used as the reference imagery. An independent test dataset of 30 points was distributed through each valley for each image. The test points were both hard and soft reference points such as road and sidewalk intersections, as well as clearly identifiable trees

Table 1. Aerial photographs used for Land Use and Land Cover (LULC) assessment

Alcalde	El Rito	Hondo	
[e] 1935 -?	[e] 1935 - ?	[e] 1935 - ?	[a] Army Map Service
[g] 1949 - December	[a] 1947 - February	[a] 1953 - October	[b] Farm Service Agency
[a] 1954 - June	[a] 1954 - May	[f] 1958/59 - July/June	[c] National Aerial Photography Program
[b] 1962 - October	[f] 1963 - May	[f] 1965 - September	[d] National Agricultural Imagery Program
[f] 1975 - June	[f] 1975 - June	[f] 1975 - September	[e] Soil Conservation Survey
[c] 1997 - October	[c] 1997 - October	[c] 1997 - October	[f] U.S. Forest Service
[g] 2005 - July	[g] 2005 - July	[g] 2005 - July	[g] U.S. Geological Survey
[d] 2014 - June	[d] 2014 - June	[d] 2014 - June	

and shrubs when no other points were available. The latitude and longitude of the test points were compared to their respective reference counterparts in the 2014 NAIP imagery to determine relative horizontal accuracy (RMSE---r).

2.3 Classification Scheme

A LULC classification scheme was developed to fit the information needs for concurrent projects involving system dynamic modeling, evapotranspiration estimation, soil moisture distribution, and water budgeting. First, the highest spatial and spectral resolution imagery (2014 NAIP) was examined to determine the maximum level of mutually exclusive classes that could be visually interpreted. Next, the lowest spatial resolution aerial photographs (1935 Soil Conservation Survey) were visually assessed to determine which classes from the maximum level could be reasonably discriminated consistently. This resulted in a three-tier hierarchical classification scheme (Table 2). To preserve the maximum level of detail consistent through all images the final classification scheme was a combination of level one and level two classes. Only Orchard, Road, Structure, and Riparian classes were identifiable at the second level of classification in all images. Thus, the classification scheme used for comparing all years of classified maps included: Irrigated Pasture (Irrigated Agriculture minus Orchard), Orchard, Non-Irrigated (Other Non-Agriculture minus Riparian), Riparian, Structure, and Road.

2.4 Digitizing and Classification

The three study sites were delineated to include areas that could potentially be irrigated by an *acequia*. The delineation started at the first upstream point of water diversion from a stream or river and generally followed either an *acequia* or an elevation contour line with the assumption that water would not flow upslope from the *acequia*. In cases where an *acequia* did not return to the stream or river, the boundaries were closed by following noticeable features in the images such as roads, arroyos, and elevation contour lines.

Features in each of the study valleys were manually digitized and classified. Topology rules were defined in a file geodatabase to restrict polygon overlap and gaps between polygons. LULC polygons were digitized at a scale of 1:2,000 starting with the 2014 images because they had the highest level of detail and subsequently working back toward 1935. The polygons were classified based on visual interpretation of the aerial photographs.

Table 2. Hierarchical classification scheme used for describing Land Use and Land Cover (LULC) in the study

Level I	Level II	Level III
Irrigated Agriculture	Row Crop	
	Orchard	
	Grass/Pasture/Alfalfa	
	Fallow	
Other Non-Agriculture	Riparian	
	Shrubland	
	Woodland	
	Pond	
	Woody-Fallow	
	Garden/Lawn	
	Outdoor Storage	
Built-Up	Structure	
	Road/Driveway	Paved Road
		Gravel Road/Driveway

Standard image interpretation techniques were used, including the consideration of tone, size, shape, texture, pattern, shadow, site, and association to differentiate land surface features (Paine and Kiser 2012). The image time-series was used as ancillary information to identify areas that were once agriculture, but had changed to woody-fallow and to help identify structures in lower spatial resolution images. Community members provided local knowledge of the study valleys to assist in classifying the three 2014 maps.

Two limitations and potential sources of error in the image classification are 1) the positional accuracy of the mosaics and 2) the aerial photographs being collected at different times in the growing season. Considerable effort was put toward georeferencing the aerial photographs; however, the photographs were not always perfectly co-registered. Aerial photos taken outside of the growing season were difficult to interpret because most vegetation is dormant, the tone of the photographs becomes more homogenous, and LULC appears to be mostly fallow fields. Since there are no alternatives to the aerial images, the registration and classification errors were accepted and reported in the thematic and positional accuracy assessments.

2.5 Thematic Accuracy Assessment

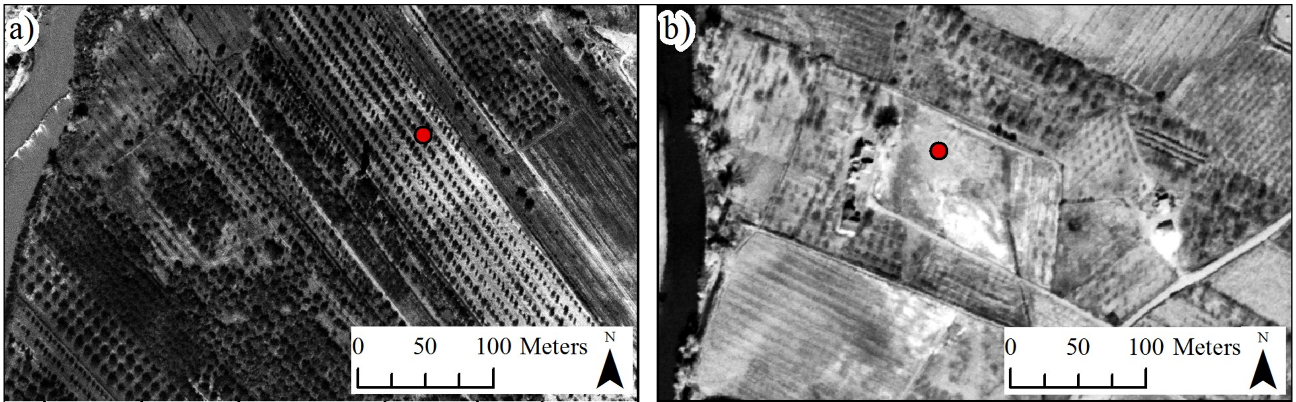
Map accuracy indicates to users the quality of the LULC analysis and explains errors in the map. Thematic LULC map accuracy assessment is commonly performed using error or population matrices (Congalton and Green 2009; Pontius and Millones 2011). These methods require some form of independent test data, either from a higher spatial resolution aerial image or from field observations. These methods, however, do not work for the current study because there are no available field observations that correspond with the image archive (1935-2014) and there are no independent higher spatial resolution aerial images to test against.

A solution to this shortfall is the use of fuzzy-set theory to assess the thematic accuracy of the LULC maps, which allows for better descriptions of the inherent heterogeneity and ambiguity of thematic maps (Gopal and Woodcock 1994). A point feature class was created using a stratified random sample of 260 points for each of the twenty-four LULC datasets. In some cases, the areal proportion of a particular class was small and the class only received one sample point. To account, accuracy assessment points were manually reallocated from the largest class by an outside analyst until there was a minimum of ten test points per class to ensure complete class representation. The random sample points were placed on top of the aerial photograph for their respective years.

The crux of the fuzzy-set accuracy approach of Gopal and Woodcock, (1994) is the use of a linguistic scale. The linguistic scale allows for qualitative assessments to be quantified and also allows for measures of heterogeneity or ambiguity within the classification rather than using a typical dichotomous measure of right or wrong (Gopal and Woodcock 1994). Each random point was evaluated and assigned a numeric value of "correctness" for each class in the classification scheme based on the linguistic scale which ranges between 1 to 5 (Table 3). Random points were considered "correct" for a class if the point received a value of 3 or higher. For example, in Figure 2a the random point received a ranking of '5' for the Orchard class and '1' for all other classes because the point clearly lies in an orchard. However, in Figure 2b, the random point is in an area that is more ambiguous, and thus received a ranking of '3' for Irrigated Agriculture, '3' for Other Non-Irrigated and '1' for the remaining classes. Using this method, it is possible for a single point to be "correct" for more than one class. The outcomes of the random point assessment were subsequently processed into tabular data used to calculate four measurements of map quality: 1) nature and distribution of errors, 2) magnitude and frequency of errors, 3) class membership across categories, and 4)

Table 3. Linguistic scale used in accuracy assessment

Assigned Value	Qualification
1	– Completely incorrect. Class label completely inappropriate
2	– Plausible but incorrect
3	– Reasonable
4	– Probably correct but not completely confident
5	– Completely correct. No doubt in the class label



a)

	Irrigated Pasture	Orchard	Other Non-Irrigated	Riparian	Road	Structure
Rank	1	5	1	1	1	1

b)

	Irrigated Pasture	Orchard	Other Non-Irrigated	Riparian	Road	Structure
Rank	3	1	3	1	1	1

Figure 2. Example of the use of the linguistic scale for accuracy assessment for an: a) homogenous/non-ambiguous area; and, b) heterogeneous/ambiguous area

class confusion and ambiguity.

The nature and distribution of errors measurement was defined by a Boolean function of correct" (linguistic scale ≥ 3) or "not correct" (linguistic scale < 3) for each random point/map classification pair and calculates individual class matches and mismatches. Magnitude and frequency of errors helps identify the seriousness of the errors in the map and how often a class is misclassified by examining the difference between the linguistic score of the map category and the highest score given to the testing point among all other categories (Gopal and Woodcock 1994). The possible values for the magnitude and frequency of errors range between -4 and 4, where 4 occurs when the correct map category received a score of 5 (completely correct) and all other categories received a score of 1 (completely incorrect). Class membership across categories addresses heterogeneity within map classes by measuring how often sample points are assigned to one class, or more than one class, and how often the points are considered matches or mismatches. The class membership results indicate conditions where class confusion occurs and where mismatches are a result of confusion within ambiguous or unambiguous areas of the map. Class confusion and ambiguity measures are similar to the commonly used error matrix, but with the addition of illustrating how often ambiguity occurs between classes.

The accuracy assessment may include some bias because the assessment was performed by the same analyst who performed the classification, albeit six months apart and without any of the polygon boundaries. The analyst was also the only available person trained in image interpretation.

3. Results and Discussion

3.1 Positional Accuracy

The RMSEr ranged between 1.65 and 3.7 meters and the horizontal accuracy ranged between 3.3 and 16.79 meters at a 95 % confidence level (Table 4). The 1935 Alcalde mosaic had the largest positional error at 16.79 meters at a 95 % confidence level; however, the radial RMSE was still comparable to the other mosaics. The 2005 images had the smallest positional error (less than 2 meters). The older aerial photograph mosaics generally had smaller positional accuracy likely from the effects of the aircraft roll, pitch, and yaw and could not be corrected even using dozens of tie points for georeferencing. Differences in spatial resolution between the reference image and the aerial photograph mosaics also affected the positional accuracy when using trees and shrubs as tie points. The positional inaccuracies primarily influenced the location of digitized roads and built structures. In cases where roads or built structures were clearly misaligned, Road and Structure polygons were digitized from an image year that had a more precise positional accuracy.

3.2 Land Use/Land Cover Classification and Change

Thematic LULC maps were produced and the area for each class was quantified for eight points in time between 1935 and 2014 for each of the three *acequia*-irrigated valleys. The manually digitized maps illustrate the major and subtle changes in the three *acequia*-

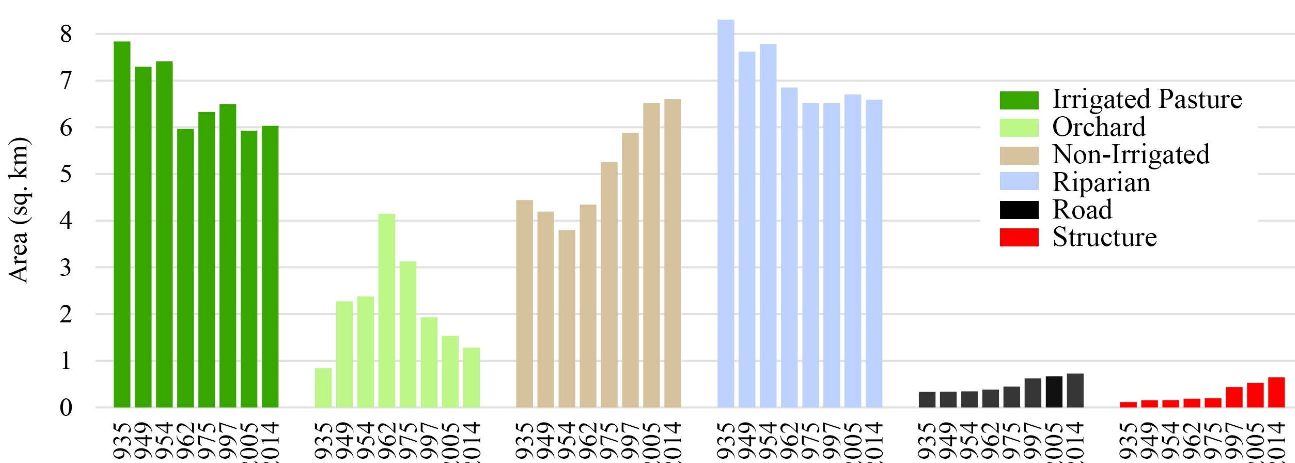
Table 4. Results of the positional accuracy assessment (in meters) of the aerial photo mosaics. The 2014 image was used as the reference image.

Alcalde			El Rito			Hondo		
Year	RMSEr	95 % CI	Year	RMSEr	95 % CI	Year	RMSEr	95 % CI
1935	3.70	16.79	1935	3.06	11.48	1935	2.51	7.70
1949	3.31	13.41	1947	3.30	13.30	1954	2.93	10.48
1954	3.38	14.01	1954	2.83	9.79	1958	2.71	9.00
1962	2.36	6.80	1963	2.23	6.09	1965	1.94	4.63
1975	2.47	7.48	1975	3.13	11.99	1975	2.14	5.59
1997	1.94	4.62	1997	2.12	5.52	1997	2.16	5.72
2005	1.75	3.76	2005	1.83	4.12	2005	1.65	3.33
2014	N/A	N/A	2014	N/A	N/A	2014	N/A	N/A

irrigated valleys. All three valleys showed increases in Structure and Road classes and decreases in Irrigated Pasture and Orchard classes. While the Structure and Road classes account for only a small percentage of the total LULC, these classes are often associated with the transition of nearby irrigated-agricultural land to non-agricultural land. A visual analysis suggests the size of agricultural fields decreased and became more fragmented between 1935 and 2014. However, this metric was not quantified because the digitized polygons were not based on a cadastral layer and some fields were aggregated when fence lines were not apparent.

The Alcalde valley had the largest changes in LULC. The Orchard class increased in area between 1935 and 1962, reaching a peak of 4.1 km2 in areal extent during the 1960s (Figure 3). However, the areal extent of orchards sharply decreased since the 1970s. The orchard decrease was largely due to a severe frost that devastated fruit trees in 1971 that have not since recovered (Yao, Walser, and Martin 2012; Ortiz et al. 2007). Many former orchards were converted to pasture/grass/alfalfa or were sub-divided for development. Channelization of the Rio Grande in the 1950s reduced natural flooding and stream meandering and reduced the riparian (or bosque) areas along the river (Scurlock 1998). Following channelization, agricultural land and orchards expanded into some former riparian areas (Figure 4). From 1975 through

Figure 3. Total Land Use and Land Cover (LULC) estimates by class for the Alcalde study site



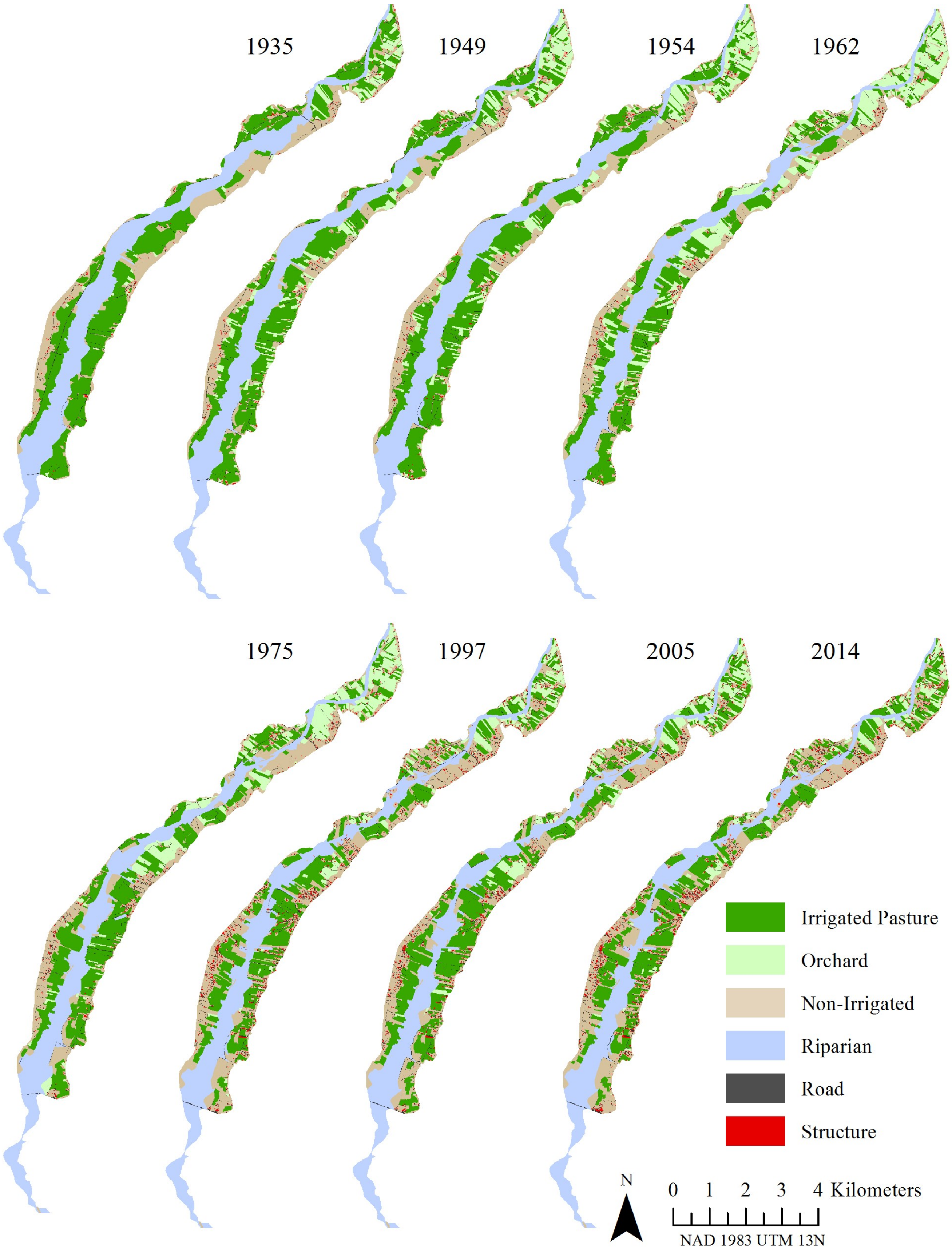


Figure 4. Land Use and Land Cover (LULC) for the Alcalde study site from 1935 to 2014

2014, Structure and Road classes increased and agricultural land converted to Non-Irrigated land. The area covered by built structures increased nearly six times the area between 1935 and 2014. Between 1962 and 2003 Ortiz et al. (2007) reported changes in land class area of -69 % (Orchard), -3 % (combined Row Crop and Pasture classes), and -3 % (Riparian), for a spatial subset of the Alcalde study site. Although our study encompassed a larger spatial extent of the valley, the results were similar for Orchard (-63 %), Irrigated Pasture (-1 %), and Riparian (-2 %) between 1962 and 2005. However, Ortiz et al. (2007) estimated a change in their Residential class of 553 %, where our analogous class of Structure increased 184 %. The difference is likely attributed to the level of detail in classification. Ortiz et al. (2007) classified an entire plot of land as Residential if a structure was located on the plot whereas we recognized the heterogeneity of plots, which would often include Structure, Road, Irrigated Pasture, and Non-Irrigated land.

The Hondo study area experienced increases in the areal extent of Road and Structure classes and decreases in the area of Irrigated Pasture (Figure 5). Road and Structure classes increased 184 % and 408 % between 1935 and 2014, respectively. Irrigated Pasture decreased by approximately 49 % or about 4.7 km2. The areal extent of the Orchard class was minimal in 1935 and has since been reduced further to only a few small plots of land. Although Irrigated Pasture has been declining since 1935, a majority of the reduction occurred after 1975 with the conversion of farmland for development (Figure 6). Between 1991 and 1997, two center-pivot irrigation systems with a diameter of approximately 750 meters were constructed near the southern portion of the study area. However, neither center-pivot appeared operational in the imagery after 2005. The areal extent of riparian land showed little change from 1935 to 2014. The opening of a ski resort nearby in the 1950s may have increased demand for development in the study area after that time. As part of a broad study on resiliency of *acequia* systems to changing climate and population, Miller (2013) classified and compared land use on a spatial subset of the Hondo study site for five land use classes between 1969 and 2010. The area for the Orchard class was similar to the current study; however, the 1935 Orchard class estimate was less, likely due to slight differences in image interpretation. The study suggested an increase in building footprints of 295 % compared to this study's estimate of 232 % between 1965 and 2014.

The El Rito valley experienced the least amount of LULC change between 1935 and 2014. El Rito has the smallest population, smallest stream flow, and is the most geographically isolated of the three study valleys. Examination of air photos of the El Rito valley revealed very few small orchards existed during the study period. The areal extent of riparian areas remained relatively unchanged and only decreased by ~0.18 km2 (Figure 7). The largest change in LULC occurred by the conversion of ~1.7 km2 of Irrigated Pasture to Non-Irrigated land (Figure 8). The area of individual fields also visually decreased, corroborating the finding of a similar study in the El Rito valley (Gonzales et al. 2013). Road and Structure classes increased in areal extent from 1935 to 2014. However, these increases were considerably smaller than the changes identified in the Alcalde and

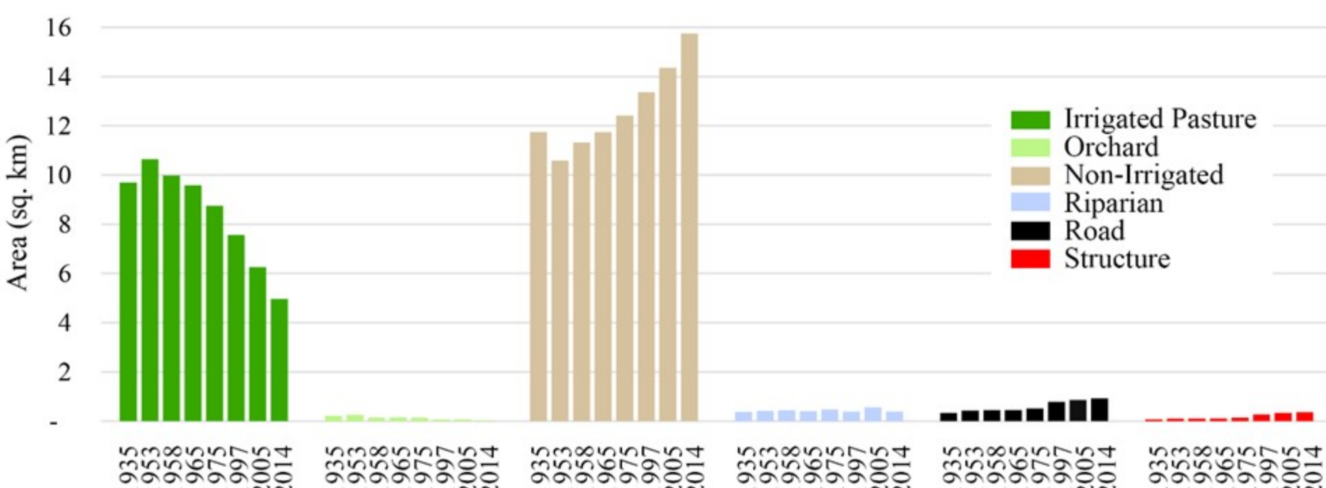


Figure 5. Total Land Use and Land Cover (LULC) estimates by class for the Hondo study site

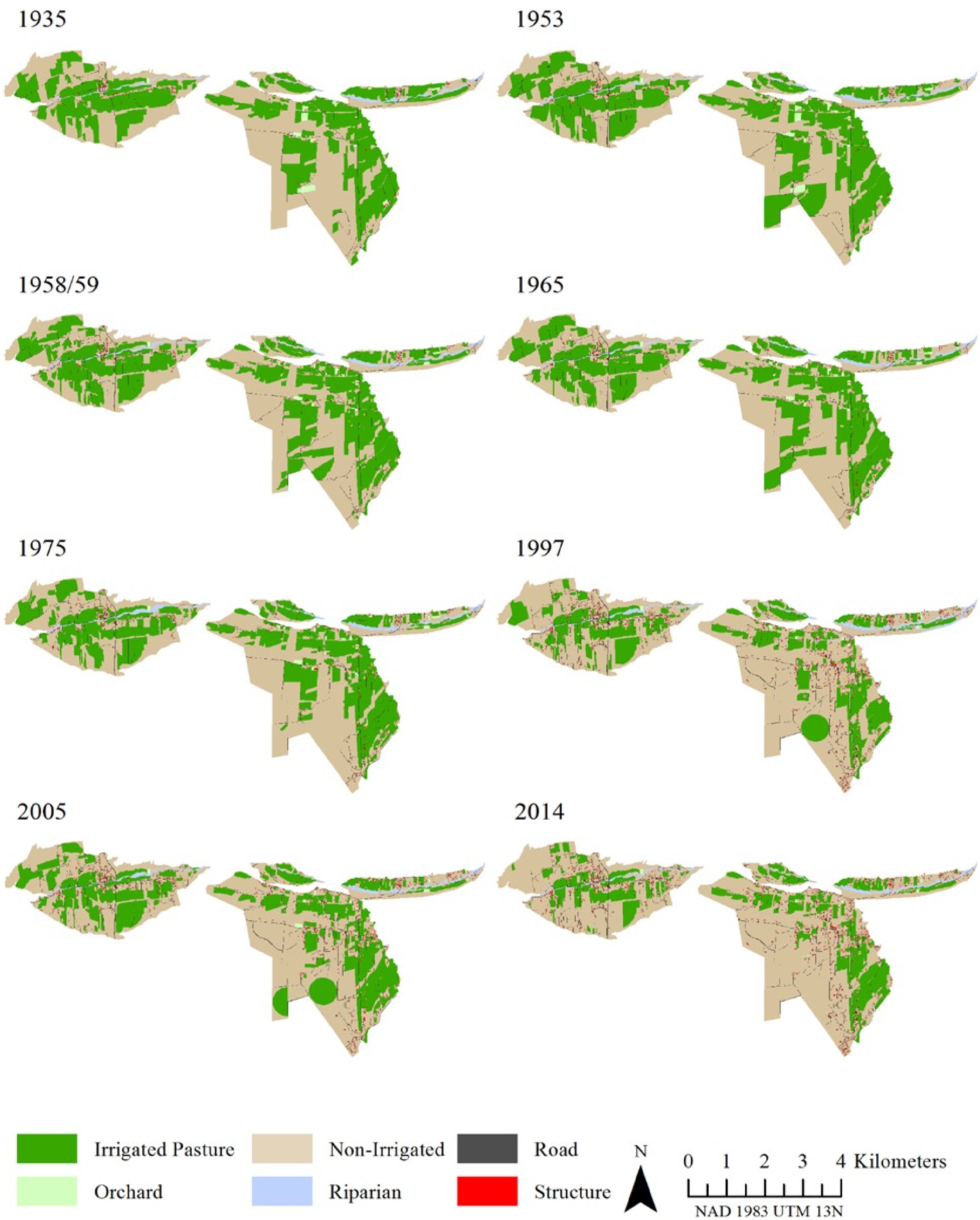


Figure 6. Land Use and Land Cover (LULC) for the Hondo study site from 1935 to 2014

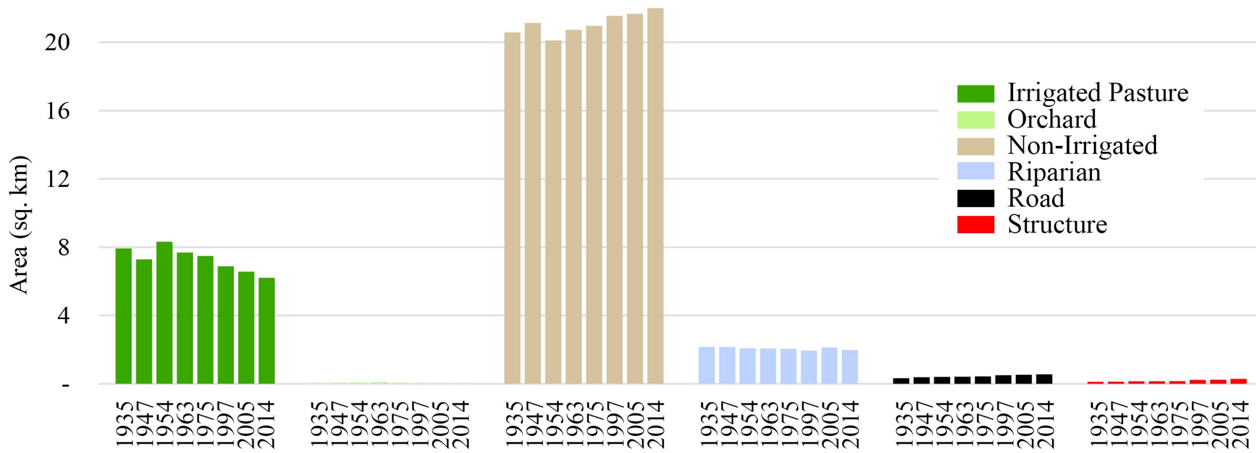


Figure 7. Total Land Use and Land Cover (LULC) estimates by class for the El Rito study site

Hondo study areas. Large areas of land were classified as Non-Irrigated on the western portion of the study location, but appear to have been irrigated at one time. Several *acequias* appear to have been abandoned in the El Rito study area prior to 1935, or were infrequently used for irrigation. A hydrographic survey map of the El Rito valley produced in 1971 (Office of the State Office of the State Engineer 1971) showed several *acequias* which were no longer active during a field visit in 2014, providing further evidence of a reduction in agricultural activities.

We assessed the percentage of change between the eight points in time for the three study areas using an approach similar to Aldwaik and Pontius (2012). The percentages of change for the Structure and Road classes were between 49 to 119% and 16 to 53%, respectively, for the three valleys for the period of 1975 to 1997 (Figure 9). Although the time periods in Figure 9 are different and not directly comparable, the figure does provide a comparison of the percentage of change for the different classes during those time periods. In order to compare and understand the rate of change in the valleys, we normalized the rate of change to reflect the average change in area per year between the different time periods (Figure 10). The rate of change for the Road and Structure class between the different time periods is low in all three sites compared to the Irrigated Pasture and Non-Irrigated classes, however, the percent change is much greater (Figure 9). This result emphasizes the importance of looking at multiple metrics of change. For more information, see Appendix tables A.1 and A.2.

Comparisons of the 2014 Cropland Data Layer (CDL), the 2011 National Land Cover Dataset (NLCD), and the localized LULC datasets from this study highlight the differences in moderate and detailed spatial resolution data (Figure 11). Both CDL and NLCD overestimated the amount of irrigated area in all three sites. For the Alcalde and Hondo study sites, the NLCD overestimated agricultural areas by 136 and 126 %, respectively. The CDL did not indicate any orchards in the three valleys. The NLCD incorporates orchards into a Cultivated Crop class along with other perennial crops. When attempting to compare the Cultivated Crop class to our Orchard class for the Alcalde site there was a 1008 % difference; therefore, we combined the Cultivated Crop, Grassland/Herbaceous, and Pasture/Hay classes for the comparison. Compared to the results from this study, developed areas in Alcalde were overestimated by 5% and 14% in the CDL and NLCD. The CLD and NLCD underestimated developed areas by 38% and 68% in the Hondo study site. El Rito developed areas were overestimated by the CDL by 6% and underestimated by 58% in the NLCD. Although the CDL and NLCD are often the only LULC datasets available, they should be used with caution for studies at a fine spatial resolution.

3.3 Thematic Accuracy

Thematic accuracy was evaluated in terms of overall accuracy, overall match, magnitude and frequency of errors, and class confusion and ambiguity. The overall accuracy for the classifications, based on a binary approach of right or wrong, ranged between 69.23 and 88.76 %; however, when calculated using the linguistic scale and the fuzzy-set approach, the overall match

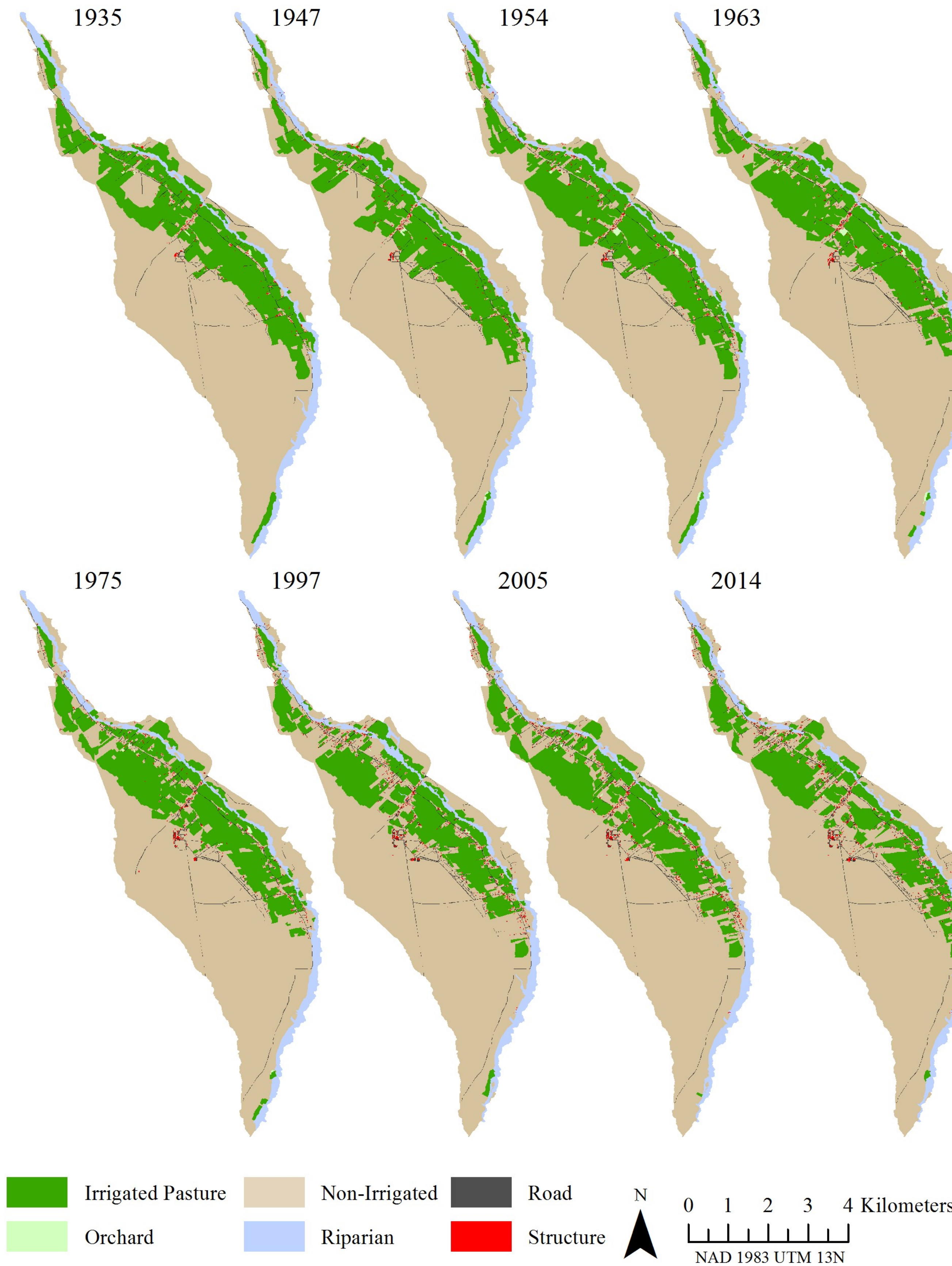


Figure 8. Land Use and Land Cover (LULC) for the El Rito study site from 1935 to 2014

Figure 9. Percent change between the different periods for a) Alcalde, b) Hondo, and c) El Rito

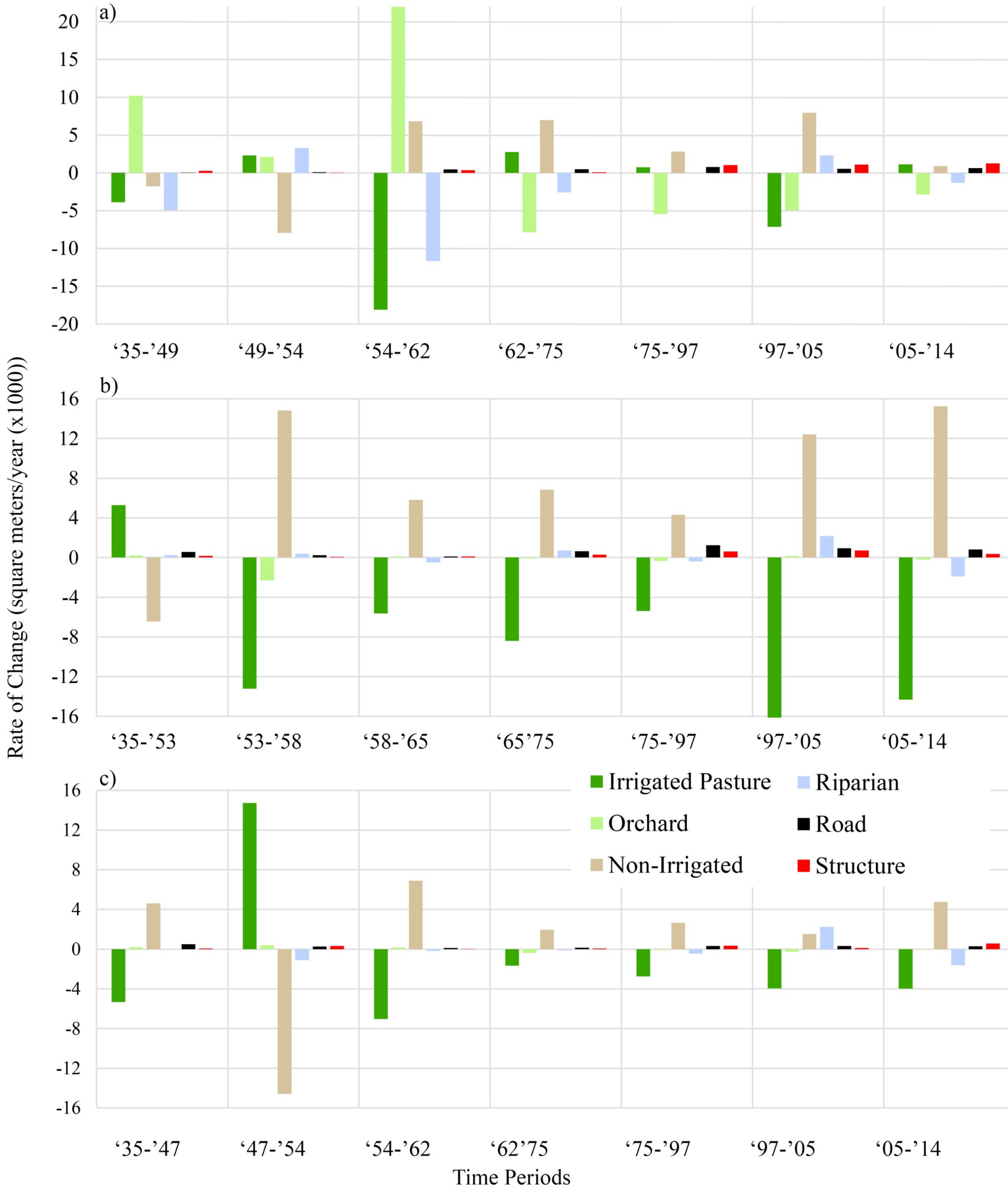


Figure 10. Normalized rate of change per year for the different periods: a) Alcalde, b) Hondo, and c) El Rito

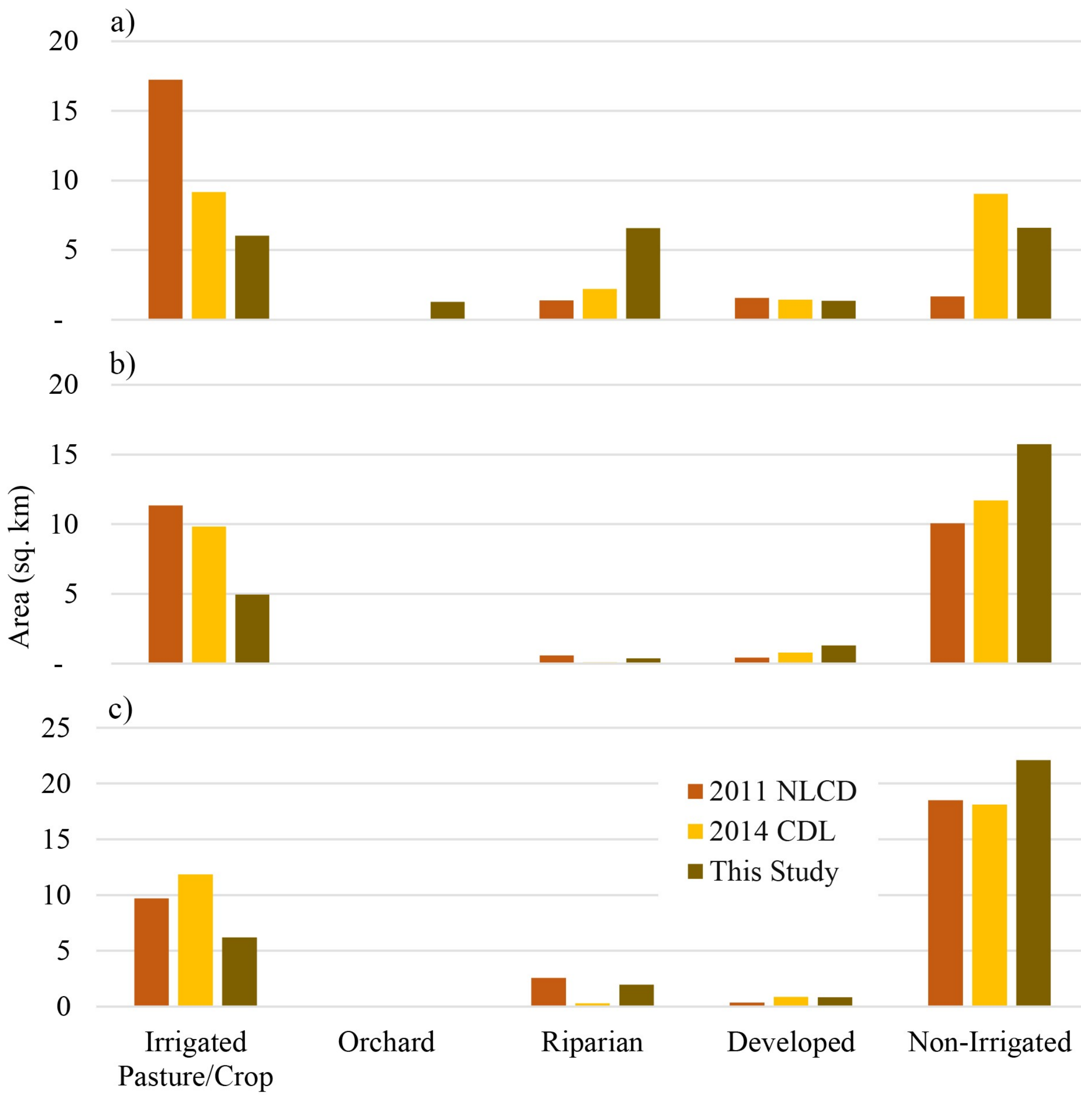


Figure 11. Comparison of estimated class areas for three different datasets: a) Alcalde, b) Hondo, and c) El Rito

increased to between 80.38 and 93.80 % (Table 5). El Rito and Hondo LULC accuracies were generally higher than Alcalde. This is likely due to the El Rito and Hondo landscapes being less complex; i.e., fewer built structures and roads and less land fragmentation. The Alcalde study site had the most complex landscape, and thus, generally lower overall accuracies. The Alcalde and Hondo study sites had considerably more development than El Rito and, in some cases, it was difficult differentiating between large lawns and irrigated pastures. Additionally, positional accuracy of the aerial photo mosaics influenced the overall accuracy outcomes.

Each accuracy assessment included an assessment of the magnitude and frequency as well as the confusion and ambiguity of map errors to provide a better understanding of the overall match. For instance, the 2005 Alcalde map had the lowest overall accuracy, but was the highest of all Alcalde maps for overall match (Table 5). The ability to assign a "correct" match to multiple classes during the accuracy assessment explains how the increase happened. However, if a testing point was given "correct" matches for multiple classes it lowered the arithmetic mean for the classes (Table 6). The frequency and magnitude measurements illustrate that most of the errors, or mismatches, for the 2005 Alcalde map were of low magnitude (-1 or -2) and are less cause for concern. Frequent high magnitude errors (mismatches receiving a score of -3 or -4) indicate more serious map errors. A closer examination of the high magnitude error in 2005 Alcalde map, as well as the other maps, found the high magnitude errors were mostly a result of positional inaccuracies in the aerial photos rather than classification errors.

Table 5. Overall thematic map accuracies for the three valleys

Alcalde			Hondo			El Rito		
Year	Overall Accuracy	Overall Match	Year	Overall Accuracy	Overall Match	Year	Overall Accuracy	Overall Match
1935	75.48%	81.99%	1935	80.77%	86.54%	1935	80.00%	87.31%
1949	75.00%	80.38%	1953	77.31%	85.77%	1947	78.46%	85.38%
1954	77.31%	83.85%	1958	85.00%	88.85%	1954	80.00%	86.54%
1962	78.38%	86.10%	1965	81.47%	86.87%	1963	83.46%	91.92%
1975	78.68%	83.72%	1975	87.69%	91.92%	1975	83.46%	86.54%
1997	70.66%	83.01%	1997	80.00%	87.31%	1997	87.69%	90.38%
2005	69.23%	87.69%	2005	85.44%	88.12%	2005	80.38%	85.38%
2014	80.00%	86.15%	2014	88.76%	93.80%	2014	86.21%	89.27%

Table 6. Frequency and magnitude of testing points for the Alcalde 2005 Land Use and Land Cover (LULC) map

		Mismatches					Matches				
Map Label	Testing Sites	-4	-3	-2	-1	0	1	2	3	4	Arithmetic Mean
Irrigated Pasture	64	1	1	1	3	3	1	11	4	39	2.797
Orchard	24	1	2	3	0	0	1	3	3	11	1.833
Non-Irrigated	70	1	1	5	5	18	4	6	13	17	1.443
Riparian	71	1	4	3	0	3	7	8	1	44	2.535
Road	16	1	0	0	0	6	1	5	1	2	1.125
Structure	15	0	1	0	2	1	1	4	1	5	1.800
Total	260	5	9	12	10	31	15	37	23	118	2.112

Confusion and ambiguity evaluation revealed the Non-Irrigated class was the most often confused or ambiguous class in the maps for all three valleys. The 2005 Alcalde map showed Riparian and Non-Irrigated classes having an unexpected level of confusion and ambiguity (Table 7). The Road class was often confused with or ambiguous to the Non-Irrigated class due to positional errors.

4. Conclusion

The objective of this research was to develop a LULC dataset that spanned multiple decades in three *acequia*-irrigated valleys in northern New Mexico. The dataset allowed for documentation of major changes in LULC for the valleys at eight points in time, spanning nine decades. The maps were produced using a consistent methodology and are thus comparable among the study valleys.

Positional error for all maps is less than 16 meters at a 95% confidence interval. Overall, thematic accuracies for the maps were between 69.2 and 88.8%, which are generally higher than those reported by the National Land Cover Dataset and are at a higher spatial resolution. These accuracies improved to between 80.4 and 93.8% match using a novel fuzzy-set approach to understanding map accuracy.

Agricultural land in the three *acequia*-irrigated valleys has steadily decreased in areal extent since 1935. There is no information available to confirm when agriculture peaked in the three valleys, so it is possible that the trend toward less agricultural LULC began before 1935. While the results corroborate anecdotal information on

Table 7. Confusion and ambiguity matrix of testing points for the 2005 Alcalde Land Use and Land Cover (LULC) map. C=confusion, A=ambiguity

Map Label	Irrigated Pasture		Orchard		Non-Irrigated		Riparian		Road		Structure		Totals	
	C	A	C	A	C	A	C	A	C	A	C	A	C	A
Irrigated Pasture	xx	xx	1	1	7	5	1	0	3	3	0	0	12	9
Orchard	1	1	xx	xx	2	1	1	0	2	1	0	0	6	3
Non-Irrigated	7	5	2	1	xx	xx	6	15	13	14	4	4	32	39
Riparian	0	0	0	0	17	15	xx	xx	0	0	0	0	17	15
Road	2	3	1	1	3	14	0	0	xx	xx	2	5	8	23
Structure	1	0	0	0	2	4	0	0	2	5	xx	xx	5	9
Total	11	9	4	3	31	39	8	15	20	23	6	9	80	98

diminishing agricultural LULC in these valleys, the work does not definitively indicate any particular period where a major shift occurred in all three valleys. Non-Irrigated land area increased in all three study sites as Irrigated Pasture and Orchard decreased. This resulted in the former agricultural land changing to shrubland, more resembling the native landscape. Structure and Road classes increased in all three valleys creating a more fragmented landscape. Future work could use the LULC information created in this study to examine the impacts of land fragmentation in the region and for change intensity analysis.

The maps and associated datasets are an important addition to the body of research focused on *acequia*-irrigated valleys, and more broadly, community managed irrigation systems around the world. The information produced in this study can be used by researchers, decision-makers, and agriculturalists to understand interactions between elements of a complex system (e.g., LULC effects on groundwater and surface water interactions and shallow groundwater recharge). Additionally, the datasets are useful as inputs into future studies examining the dynamics of change in these valleys and similar valleys in New Mexico and throughout the globe. Few research projects attempt the methodology used in this project because of the immense time cost associated with georeferencing and digitizing large areas at spatial resolutions under 10 meters. While much effort was spent on making this analysis as objective as possible, image interpretation is inherently subjective and repeatability difficult. One option for future additions to this LULC dataset is to use supervised classification of high spatial resolution satellite imagery (e.g., < 2 meters), which has an advantage of being slightly more automated and less subjective.

Acknowledgement

This project was funded by the National Science Foundation's Program on the Dynamics of Coupled Natural & Human Systems; grant #1010516.

References

Ackerly, N. W., W. Maltonic, M. Ernst, J. Wakeman, and L. Lopez. 1994. *Acequia Systems of the Velarde Region: North-Central New Mexico*, 3 Vols., NM Historic Preservation Division, Santa Fe, NM.

Aldwaik, S. Z., and R. G. Pontius. 2012. Intensity analysis to unify measurements of size and stationarity of land changes by interval, category, and transition. *Landscape and Urban Planning* 106(1): 103-114.

Anderson, J. R., E.E. Hardy, and J.T. Roach. 1976. A land use and land cover classification system for use with remote sensor data. *U.S. Geological Survey Professional Paper* 964.

Brown, J. R., and J. A. Rivera. 2000. *Acequias de comun*: The tension between collective action and private property rights. Paper read at 8th Biennial Conference of the IASCP; Constituting the Commons: Crafting Sustainable Commons in the New Millennium.

Congalton, R. G., and K. Green. 2009. Assessing the Accuracy of Remotely Sensed Data: Principles and

Practices. 2nd ed. Boca Raton, Florida, USA: CRC press.

Fernald, A., S. Guldan, K. Boykin, A. Cibils, M. Gonzales, B. Hurd, S. Lopez, C. Ochoa, M. Ortiz, and J. Rivera. 2015. Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences* 19(1): 293.

Fernald, A. G., T. T. Baker, and S. J. Guldan. 2007. Hydrologic, riparian, and agroecosystem functions of traditional *acequia* irrigation systems. *Journal of Sustainable Agriculture* 30(2): 147-171.

FGDC. 1998. *Geospatial Positioning Accuracy Standards, part 3: National Standard for Spatial Data Accuracy*. Washington D.C. Federal Geographic Data Committee Report No STD-007.3-1998.

Gonzales, M., J. A. Rivera, J. J. García, and S. Markwell. 2013. Qualitative and visualization methodologies for modeling social-ecological dimensions of regional water planning on the Rio Chama. *Journal of Contemporary Water Research & Education* 152(1): 55-68.

Gopal, S., and C. Woodcock. 1994. Theory and methods for accuracy assessment of thematic maps using fuzzy sets. *Photogrammetric Engineering and Remote Sensing* 60(2).

Guldan, S. J., A. G. Fernald, C. G. Ochoa, and V. C. Tidwell. 2013. Collaborative community hydrology research in Northern New Mexico. *Journal of Contemporary Water Research & Education* 152(1): 49-54.

Homer, C., J. Fry, and C. Barnes. 2012. The National Land Cover Database: US Geological Survey Fact Sheet 2012–3020.

Menzel, L., J. Koch, J. Onigkeit, and R. Schaldach. 2009. Modelling the effects of land-use and land-cover change on water availability in the Jordan River region. *Advances in Geosciences* 21: 73-80.

Miller, A. R. 2013. Assessing change and resilience in a northern New Mexico *acequia* irrigation community, University of New Mexico.

National Climatic Data Center. 2016. Climate Data Online 2016 [cited December 2016]. Available from https://www.ncdc.noaa.gov/

Ochoa, C. G., S. J. Guldan, A. F. Cibils, S. C. Lopez, K. G. Boykin, V. C. Tidwell, and A. G. Fernald. 2013. Hydrologic connectivity of head waters and floodplains in a semi-arid watershed. *Journal of Contemporary Water Research & Education* 152(1): 69-78.

Office of the State Engineer. 1971. Rio Chama Hydrographic Survey - El Rito Section. Santa Fe, New Mexico.

Ortiz, M., C. Brown, A. Fernald, T. T. Baker, B. Creel, and S. Guldan. 2007. Land use change impacts on *acequia* water resources in northern New Mexico. *Journal of Contemporary Water Research & Education* 137 (1): 47-54.

Paine, D. P., and J. D. Kiser. 2012. *Aerial Photography and Image Interpretation*. 3rd ed. Hoboken, New Jersey: John Wiley & Sons.

Pontius, R. G., and M. Millones. 2011. Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. *International Journal of Remote Sensing* 32(15): 4407-4429.

Rebelo, L.-M., C. M. Finlayson, and N. Nagabhatla. 2009. Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management* 90(7): 2144-2153.

Rivera, J. A. 1998. *Acequia Culture*. Albuquerque, New Mexico: UNM Press.

Rodrâiguez, S. 2006. *Acequia: Water Sharing, Sanctity, and Place*. Santa Fe, New Mexico: School for Advanced Research Press.

Saha, G., S. Paul, J. Li, F. Hirshfield, and J. Sui. 2012. Investigation of land-use change and groundwater–surface water interaction in the Kiskatinaw River watershed, Northeastern British Columbia (Parts of NTS 093P/01,/02,/07–/10). Geoscience BC Summary of Activities: 2013-1.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* 11(10): 1577-1593.

Scurlock, D. 1998. From the Rio to the Sierra: an environmental history of the Middle Rio Grande Basin. US Department of Agriculture, Forest Service. Fort Collins, CO. General Technical Report RMRS-GTR-5. 440.

Stehman, S. V., J. Wickham, J. Smith, and L. Yang. 2003. Thematic accuracy of the 1992 National Land-Cover Data for the eastern United States: Statistical methodology and regional results. *Remote Sensing of Environment* 86(4): 500-516.

Turner, B. L., V. Tidwell, A. Fernald, J. A. Rivera, S. Rodriguez, S. Guldan, C. Ochoa, B. Hurd, K. Boykin, and A. Cibils. 2016. Modeling *acequia* irrigation systems using system dynamics: Model development, evaluation, and sensitivity analyses to investigate effects of socio-economic and biophysical feedbacks. *Sustainability* 8(10): 1019.

US Department of Agriculture. 2015. National Agriculture Imagery Program (NAIP) Information

Sheet.

Weston Solutions. 2002. *Acequia* Geographic Information System Inception Phase Report. Seattle, Washington.

Wickham, J., S. Stehman, J. Fry, J. Smith, and C. Homer. 2010. Thematic accuracy of the NLCD 2001 land cover for the conterminous United States. *Remote Sensing of Environment* 114(6): 1286-1296.

Yao, S., R. Walser, and C. Martin. 2012. Evaluation of eight apple cultivars and two training systems in northern New Mexico: NM State University, Agricultural Experiment Station, College of Agricultural, Consumer and Environmental Sciences.

Zhang, Y.-K., and K. Schilling. 2006. Effects of land cover on water table, soil moisture, evapotranspiration, and groundwater recharge: a field observation and analysis. *Journal of Hydrology* 319 (1): 328-338.

Appendix

Table A.1 Area (sq. meters) for the different Land Use and Land Cover (LULC) classes for the three study sites

		1935	1949	1954	1962	1975	1997	2005	2014
Alcalde	Irrigated Pasture	7,838,153	7,295,844	7,411,330	5,964,409	6,327,790	6,494,384	5,925,585	6,030,677
	Orchard	843,485	2,271,631	2,377,896	4,144,421	3,125,781	1,928,653	1,535,616	1,281,646
	Non-Irrigated	4,441,337	4,194,046	3,797,890	4,345,383	5,255,653	5,878,246	6,517,164	6,602,059
	Riparian	8,304,148	7,619,063	7,785,211	6,851,925	6,519,601	6,514,527	6,702,665	6,589,056
	Road	332,084	338,100	344,132	381,761	445,755	621,390	666,247	725,748
	Structure	114,247	154,771	156,995	185,555	198,873	436,254	526,178	644,268

		1935	1953	1958	1965	1975	1997	2005	2014
Hondo	Irrigated Pasture	9,691,810	10,641,929	9,981,204	9,587,262	8,748,127	7,560,793	6,250,934	4,960,897
	Orchard	219,189	256,445	141,707	148,987	139,537	62,536	74,514	55,351
	Non-Irrigated	11,746,177	10,587,516	11,328,440	11,734,939	12,419,238	13,365,938	14,358,349	15,730,956
	Riparian	373,601	417,569	436,931	401,867	472,272	385,636	558,689	388,178
	Road	327,902	427,135	439,354	447,669	511,909	782,288	857,083	931,256
	Structure	71,574	99,660	102,618	109,530	139,170	273,063	330,683	363,614

		1935	1947	1954	1963	1975	1997	2005	2014
El Rito	Irrigated Pasture	7,924,662	7,285,325	8,316,533	7,683,337	7,483,825	6,880,285	6,564,298	6,205,508
	Orchard	26,038	48,793	76,503	91,890	46,573	30,345	10,355	10,123
	Non-Irrigated	20,578,594	21,130,686	20,108,794	20,729,864	20,964,202	21,545,092	21,666,001	22,094,209
	Riparian	2,158,095	2,156,433	2,078,060	2,062,233	2,048,169	1,943,872	2,124,060	1,978,938
	Road	324,798	382,754	402,163	413,186	430,446	500,338	526,254	551,568
	Structure	111,925	120,121	142,058	143,603	150,896	224,180	233,142	283,766

Table A.2 Percent of change for the different classes between the different time periods for the three study sites

		'35-'49	'49-'54	'54-'62	'62-'75	'75-'97	'97-'05	'05-'14
Alcalde	Irrigated Pasture	-7%	2%	-20%	6%	3%	-9%	2%
	Orchard	169%	5%	74%	-25%	-38%	-20%	-17%
	Non-Irrigated	-6%	-9%	14%	21%	12%	11%	1%
	Riparian	-8%	2%	-12%	-5%	0%	3%	-2%
	Road	2%	2%	11%	17%	39%	7%	9%
	Structure	35%	1%	18%	7%	119%	21%	22%
		'35-'53	'53-'58	'58-'65	'65-'75	'75-'97	'97-'05	'05-'14
Hondo	Irrigated Pasture	10%	-6%	-4%	-9%	-14%	-17%	-21%
	Orchard	17%	-45%	5%	-6%	-55%	19%	-26%
	Non-Irrigated	-10%	7%	4%	6%	8%	7%	10%
	Riparian	12%	5%	-8%	18%	-18%	45%	-31%
	Road	30%	3%	2%	14%	53%	10%	9%
	Structure	39%	3%	7%	27%	96%	21%	10%
		'35-'47	'47-'54	'54-'63	'63-'75	'75-'97	'97-'05	'05-'14
El Rito	Irrigated Pasture	-8%	14%	-8%	-3%	-8%	-5%	-5%
	Orchard	87%	57%	20%	-49%	-35%	-66%	-2%
	Non-Irrigated	3%	-5%	3%	1%	3%	1%	2%
	Riparian	0%	-4%	-1%	-1%	-5%	9%	-7%
	Road	18%	5%	3%	4%	16%	5%	5%
	Structure	7%	18%	1%	5%	49%	4%	22%