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# Hydrological, ecological, land use, economic, and sociocultural evidence for resilience of traditional irrigation communities in New Mexico, USA

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## Abstract

Southwestern US irrigated landscapes are facing upheaval due to climate change-induced water scarcity and economic change-induced land use conversion. Clues to community longevity are found in the traditionally irrigated valleys of northern New Mexico. Human systems have interacted with hydrologic processes over the last 400 yr in river fed irrigated valleys to create linked systems. In this study, we asked if concurrent data from multiple disciplines show that human adapted hydrologic and socioeconomic systems have created conditions for resilience. We identify and describe several areas of resilience: hydrological, ecological, land use, economic, and sociocultural. We found that there are multiple hydrologic benefits of the water seepage from the traditional irrigation systems; it recharges groundwater that recharges rivers, supports threatened biodiversity by maintaining riparian vegetation, and ameliorates impacts of climate change by prolonging streamflow hydrographs. In terms of land use and economics, place-based adaptability manifests itself in transformations of irrigation infrastructure and specific animal and crop systems; as grazing has diminished over time on public land watersheds, it has increased on irrigated valley pastures while outside income allows irrigators to retain their land. Sociocultural evidence shows that traditional local knowledge about the hydrosocial cycle of acequia operations is a key factor in acequia resilience. When irrigators are confronted with unexpected disturbances or changing climate that affect water supply, they adapt specific practices while maintaining community cohesion. Our ongoing work will quantify the multiple disciplinary components of these systems, translate them into a common language of causal loop diagrams, and model future scenarios to identify thresholds and tipping points of sustainability. Early indications are that these systems are not immune to upheaval, but have astonishing resilience.





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## 1 Introduction

In arid regions around the world, traditional irrigation systems have evolved to maintain community stability despite conditions of prolonged drought and climate variability. In the upper Rio Grande of the United States, *acequia* is the Spanish word for both the physical irrigation works and the water management institution governed by the users who divert water from rivers and streams dependent on mountain snowpack in the uplands bioregion of north-central New Mexico and southern Colorado. The word acequia is originally derived from Arabic *as-sāqiya* with the same meaning as a water conduit or irrigation canal. Transplanted to the New World from Iberia some four centuries ago by way of the Camino Real de Tierra Adentro heading north from Mexico City to Santa Fe, these community irrigation systems have developed complex self-maintaining interactions between culture and nature that enable drought survival while providing many other cultural, ecosystem, and economic benefits. Many of these benefits are tied to the connections between landscape and community. At the heart of the system, water from the river is diverted onto fields for crops, into ponds for animals, and across valleys supporting riparian vegetation. The grazing and wildlife on the upper watershed rely on forest and rangeland plant communities, the management of which determines runoff to the valley below. Community dynamics that use the valley and watershed for livelihoods determine water distribution that impacts the hydrologic cycle. Importantly, water that seeps from acequias and fields recharges groundwater that in turn provides river flow for downstream users (Fernald et al., 2010).

Today, these traditional communities are facing new socioeconomic and natural resource pressures that threaten their ability to function as originally designed. Like counterparts elsewhere in the world, unpredictable and/or limited water supplies are a common challenge faced by traditional irrigation systems that depend on surface water and gravity flow technologies. Under conditions of warming temperatures and reduced snow storage during winter months, river flow is expected to decrease, and snowmelt runoff has already begun to arrive earlier in the spring, trends that are expected to





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exacerbate water scarcity in the western United States (Barnett et al., 2008). Among other threats that acequias are facing today, most are directly or indirectly related to increasing population and urbanization (Cox and Ross, 2011; Ortiz et al., 2007; Rivera, 1998).

In the face of these threats, acequia communities appear to be particularly well suited to persevere. They have established connections between the sporadic hydrology and vibrant human communities to impart continuity and longevity. These connections center upon the acequia itself, the physical structure to deliver water from river to field, and the human system to manage the water delivery and use (Fig. 1). We posit that the hydrology cannot be understood without the human connection and the human dynamic cannot be characterized without the hydrology.

The goals of this study are to connect human and natural systems using real data that crosses over the intersecting disciplines, showing sustainability and adaptive capacity or non-sustainability and tipping points. This study confronts the hypothesis that the resilience of the system is integrally tied to the concurrent acequia system development of community dynamics and hydrologic processes. We identify resiliencies tied to hydrosocial changes that can be characterized only by including the multiple interacting disciplines of the hydrologic and human systems. For expected hydrologic-social changes there are resident resiliencies that we measure and document. Our approach in this paper is to show the foundational evidence linked by acequia system universal themes.

## 2 Hydrologic and ecological resilience due to irrigation seepage

Overall, the human system of acequia irrigation ditches impacts hydrologic processes by increasing water distribution across the irrigated landscape. Hydrograph alterations due to climate change are ameliorated by seepage from acequia irrigation systems that recharges groundwater and provides return flow to rivers. Biological diversity is threatened by land use change, yet acequia system contributions of water to maintain



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riparian areas help mitigate the loss of these habitats in adjacent landscapes. At the regional scale, return flow to the rivers from groundwater ameliorates impacts of climate change on snowmelt hydrographs that are earlier and shorter due to increasing temperatures. The hydrology of these rivers and valleys cannot be fully understood without including the human created irrigation system. Acequia systems have multiple hydrologic benefits that accentuate resilience.

### 2.1 Ditch and field seepage, groundwater recharge, and river return flow

In many watersheds of the southwestern United States, snow-melt runoff is the main source of streamflow during spring and summer. In these watersheds, agriculture is confined to narrow irrigated floodplains along rivers or creeks. That is the case of traditional irrigation systems in watersheds of northern New Mexico, where relatively small irrigated valleys are spread on the alluvial floodplain along the main river systems. In many of these agricultural valleys river water is gravity-driven into irrigation canals (acequias) that run along the valley where water is either diverted into smaller irrigation canals or applied directly to crop fields in the form of flood or furrow irrigation (Fernald et al., 2010).

Farming on these alluvial floodplains is dependent on the connectivity between surface water and shallow groundwater, particularly in the forms of precipitation, runoff and infiltration processes in the upper watershed and their linkages with streamflow, irrigation, and aquifer recharge in the lower valleys. Results from our combined intensive field monitoring and modeling approach indicate that there is a strong hydrologic connectivity between snow-melt driven runoff in the headwaters and recharge of the shallow aquifer in the valleys, mainly driven by the use of traditional irrigation systems (Ochoa et al., 2013a). For example, Fig. 2 shows results from one of our study sites illustrating that during the irrigation season (April–October), shallow groundwater levels rise in response to irrigation percolation and canal seepage. Then in the late season, without irrigation, the river acts as a drain and starts receiving some delayed return flow from groundwater that was temporarily stored in the shallow



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aquifer during the irrigation season. Also, similar patterns in seasonal shallow aquifer recharge have been observed in wells located in dry land at distances of about 1 km away from the main irrigation canal and from any irrigated fields (Ochoa et al., 2013b). Conservation of this seasonal aquifer recharge provides several ecosystem functions including water quality enhancement, riparian habitat support, and river connection to the groundwater. It also supports important economic and ecological functions downstream through temporary storage and release processes.

The hydrologic connectivity between upland water sources and irrigated valleys through the shallow groundwater system can be important for understanding the hydrologic resilience of agroecosystems in the face of climate variability. Human-induced changes (e.g., changes in land use or in technology) and natural processes (e.g., severe drought) can modify the spatial and temporal patterns of hydrologic connectivity in a given landscape. For instance, a significant change in land use from agriculture to residential and/or a big shift in irrigation technology that favors changing from the use of traditional flood to drip irrigation may severely affect the recharge of the local aquifer, the delayed return flow back to the river, and the important economic and ecological functions that are dependent on these currently functional agroecosystems in the southwest.

### 2.2 Climate change runoff impacts ameliorated by groundwater return flow

A large proportion of the water available to acequia communities for irrigation is supplied by melting of the annual snowpack in high-elevation watersheds above acequia valleys. Climate warming and changes in the quantity and temporal frequency of precipitation threatens the accumulation of snow, timing of melt and thus the timely delivery of water for irrigation. In a case study of the effects of climate warming on streamflow in the El Rito watershed, we used downscaled data from the MIROC5 (Model for Interdisciplinary Research on Climate) climate model as input to the Snowmelt Runoff Model (SRM: Martinec et al., 2008). We selected MIROC5 (run 1) for the case study, because the estimates of temperature and precipitation changes





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between the late 20th and late 21st centuries provided by this model represent the central tendency of an ensemble of changes assessed from 60 Coupled Model Intercomparison Project 3 (CMIP3) and CMIP5 climate models. SRM is a simple degree-day model that simulates streamflow as a function of temperature, precipitation and snow cover. In the example presented here, we simulated streamflow in a relatively productive year (1994) and then used the parameters from the 1994 simulation to drive the model with data from 2095 to 2099.

From the example presented here (Fig. 3), warmer temperatures predicted by the MIROC5 model are likely to cause an earlier occurrence of peak runoff from snowmelt. Historical data show that over the last few decades of the C20th, peak runoff usually occurs in over a four week period between 15 April and 15 May. By the end of the C21st peak runoff is predicted to occur between 1 and 30 April.

Although peak streamflow is predicted to occur earlier in the year and the volume of water delivered during peak streamflow is potentially greater than historical years, the connectivity between snowmelt-driven runoff and aquifer recharge provided by acequia flood irrigation provides a means for mitigating the potential for flooding and/or loss of water. The temporary storage and release of water provided by flood irrigation tradition of the acequia systems is important locally for ensuring water supply longevity through the growing season within the acequia valley itself. The effects of runoff modulation by acequias are also anticipated to extend beyond the local scale to the regional scale as illustrated by a conceptual diagram of the Embudo Station stream gauge hydrograph on the Rio Grande (Fig. 4).

### 2.3 Ecological species richness

Future land-use scenario impacts on species habitat were analyzed in the regional study area. We compared future land-use scenario impacts on the upper Rio Grande river basin using the EPA Integrated Climate and Land Use Scenarios (ICLUS) dataset (Bierwagen et al., 2010). The ICLUS scenarios are divided by two dimensions indicating pressures and driving forces behind the scenarios. The “A” scenarios are





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driven by economic forces while "B" scenarios are driven by environmental forces (Fig. 5, $X$ axis). Scenarios with 1 attached indicate global development and 2 indicates regional development. The Base Case (BC) scenario uses a current business as usual approach. We measured future urban grow-out effects on 19 biodiversity metrics derived from the Southwest Regional Gap Analysis Project (SWReGAP) habitat models (Boykin et al., 2007). Our effort identifies the areas and quantifies the magnitude of these changes depending on the future scenarios and the metric.

Relative percent loss of natural area and amount of square kilometers of natural area converted to urban area was tabulated for all 19 biodiversity metrics (Boykin et al., 2013). One metric (bird richness) was the focus of this analysis with the metric classified into four equal interval species richness categories including low species richness (Richness Class 1), moderate-low species richness (Richness Class 2), moderate-high species richness (Richness Class 3), and high species richness (Richness Class 4) (Fig. 5). For bird species richness under scenario BC, richness classes had 23–39 % relative loss. Under scenario A1, all class losses were approximately 24 %. Scenario A2 ranged from 4.4 to 25.6 % loss with class 1 the highest. Scenario B1 losses ranged from 2.2 to 11.2 % with richness class 1 the highest. Scenario B2 ranged from 0.8 to 11.7 % with class 1 the highest. Scenario BC (Base Case) represents the total highest relative percent decrease in natural area for this metric while scenario B2 represents the total lowest relative percent decrease in natural areas (Fig. 5). In the Base Case scenario, a large percentage of habitat including acequia-irrigated fields and riparian area that support species diversity are lost to urban development. The scenarios driven by economic forces (A) still lose a large percentage of habitat, while those driven by environmental forces (B) lose the least amount of habitat.





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## 3 Place-based adaptation to changing land use and economics

In this section we provide quantified components of grazing, farming, economics and land use changes showing that if communities can stay connected to the acequia landscape, they can adapt and survive. Region-wide livestock numbers have fallen since the mid-1990s, yet strong links between livestock-raising and irrigated farming contribute to the cohesion of acequia communities. Streamflow is highly variable and the recent past includes very dry years, but income added from outside of farming provides a coping strategy to weather periods of drought. Acequia farming has lost its role as main provider of food for the community, but demand from regional urban areas for local food along with the availability of alternative crops provide options for adaptive responses. Drought and climate change threaten continued crop production, but a history of adaptations as well as maintenance of acequia infrastructure and farm plot arrangements indicate flexibility to transform and meet future challenges.

### 3.1 Upland grazing

Livestock-raising and irrigation farming are tightly intertwined in traditional Hispanic rural communities of northern New Mexico. Owning livestock is vital to acequia community families; it is a way of reconnecting to their heritage (Eastman and Gray, 1987) and "an essential component of [their] historic persistence and self-reliance" (Cox, 2010; p. 65). Spanish deposition of farming lands included grazing rights on adjoining uplands, which constitutes a testament of the historical importance ascribed to livestock-raising as a means of community financial stability (E. Gomez, personal communication, 2012). Region-wide reductions in cattle numbers have become more pronounced since the mid 1990s (Fig. 6) and have been interpreted as an early indicator of decreased economic stability of acequia communities (Cox, 2010; E. Gomez, personal communication, 2012). Although this phenomenon varies locally (Raish and McSweeney, 2003; Cox, 2010; S. Lopez, unpublished data), these trends could point to the weakening of an activity that has historically provided a natural





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link between valleys and uplands and has contributed to the cohesion of acequia communities.

### 3.2 Settlement morphology and agriculture in the Rio Arriba

Future water demands in urban centers and the potential for long term drought will continue to threaten the resiliency of traditional acequia based communities in the upper Rio Grande basin. In the future, acequia communities may need to respond to such pressures though adaptation of land use and agricultural practices at the community scale. In order to understand the resiliency and adaptive capacity of acequia based community systems, we focused research on how acequia settlements have adapted over time in response to economic and environmental factors. For a timeline, we examined the evolution of land use change over a period of approximately 75 yr by analyzing agricultural census data for Rio Arriba County and comparing that data to both qualitative and quantitative data at the community scale for key villages such as Alcalde, Hernandez, Chamita, and El Rito. For the purpose of this article, we will exemplify the findings of land use change in the community of Alcalde, New Mexico, compared to changes in agricultural practices in Rio Arriba County as a whole. An examination of historic land use change can provide land management strategies to acequia communities for coping with the potential impacts of climate change and drought.

The methodology used to examine the evolution of land use change in Alcalde began with a qualitative visual analysis by mapping key physical elements of built and natural systems that were traced over 1935 aerial photography (Earth Data Analysis Center, 2010) and compared to 2011 aerial photography of the same geographic layers. Initial findings from mapping community scale morphology revealed an increase in farm plot size, a dispersed settlement pattern, less crop diversity, and a restricted channelized riparian condition (Fig. 7). From this initial phase of qualitative mapping analysis, we expanded the methodology to include a quantitative analysis of land use change at the county scale by examining agricultural census data to track changes in farm size as





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well as livestock and cropping patterns from 1930 to 2007. In addition, we conducted a mapping inventory of portions of the Alcalde community to document shifts in parcel size and cropping patterns from two key data sources: the 1880–1930 small holdings claims land patent surveys for Alcalde from the General Land Office of the United States; and 2010 parcel data from the Rio Arriba County Assessor's Office (Rio Arriba County Assessor's Office, 2013). This procedure allowed us to compare land use change at the county scale to land use change for Alcalde at the community scale (Fig. 8).

#### 3.2.1 Data: land use change in Rio Arriba County 1935–2010

To examine changes in agricultural practices and land use conditions in Rio Arriba County, we examined socioeconomic and agricultural data from both the decennial US census as well as the agricultural census for Rio Arriba County. We began with data in the 1930s to provide a baseline of pre-WW II agricultural conditions when people still lived off the land. The construction of Los Alamos National Laboratory in 1943 transformed the economy from agropastoral subsistence farming to wage-based off-farm employment. In 1935, there were 3500 farms documented, 1400 of which were between three and nine acres, and another 600 farms ranging from 10 to 19 acres accounting for 57 % of the farms in that year (Agricultural Census for Rio Arriba, 1935) (Fig. 9). In subsequent decades, agricultural parcels would increase in size; 1200 farms were reported in 1964, 380 of which were between one and nine acres in size, and another 400 farms were classified as having from 10 to 49 acres making up 65 % of the farms in that year (Rio Arriba Agricultural Census, 1964). In 2007, of the nearly 1,400 farms reported to the US Census, the range in parcel size remained consistent with the 1960s (Fig. 10). The overall decline in small farm size farms from 1935 to 1964 suggests a shift in the agricultural system from a subsistence form of agriculture to one of supplemental income.

In addition to shifts in farm parcel size, for the same period, we examined changes in livestock management practices at the county scale. In the last 75 yr, there has been a major transformation from a sheep economy to a cattle-based economy which may suggest a change in cropping patterns in acequia communities. In the 1930s, sheep and chickens significantly outranked cattle production. However by 2007, cattle production in Rio Arriba County far exceeded any other livestock type which suggests a demand for pasture grass production on acequia irrigated agricultural land (Fig. 11). Data suggest that small farm parcels generally increased in size after WW II along with a shift to cattle based agricultural economy which may have resulted in the increase of pasture grass production in irrigated land.

In the next step, we then developed a community mapping process to analyze if factors identified in the agricultural census impacted land use change at the community scale. Community mapping for documenting land use change for Alcalde begins by comparing changes in agricultural parcel size and changes in agricultural land use from 1935 to 2011. Small holding claim land patent surveys of agricultural parcels from 1880 to 1930 were mapped over 1935 aerial photos to establish data for crop land cover, agricultural parcel size, and riparian land form. Historic data were then compared to existing land use conditions from 2011 aerial photography and the 2010 land parcel data from the Rio Arriba County Assessor's Office (Fig. 12). Findings on land use change in Alcalde included a decrease in the acreage of field crops from 84.5 to 30 acres, an increase of development into the irrigable farm land of 42.3 acres, and a decrease in the average agricultural parcel size from 3.6 to 1.9 acres (Table 1). Also, the channelization of the Rio Grande River increased the bosque (riparian) vegetation in the study area by approximately 14.9 acres during the same period.

### 3.2.2 Acequia resilience in the face of economic and land use changes

The land use change in Alcalde has been similarly documented for other communities in the Rio Chama basin of Rio Arriba County: Hernandez, Chamita, and El Rito. Since WW II, acequia communities moved away from small tract subsistent agriculture to an agricultural system based on cattle production in order to maintain resiliency in the irrigation system. The move from field crop diversity to pasture grasses for





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livestock feed provided economic gain for farmers to participate in the post-WW II wage economy while maintaining irrigable acequia farmland. The challenge today of prolonged drought and climate change coupled with the reduction of grazing animal units in US Forest Service land will increase pressure on the grazing system. However, acequia communities have the opportunity to develop strategies for adapting the existing land use configuration of irrigable farmland into a system capable of dealing with the potential impacts of prolonged drought and climate variability. Possible strategies include value added crop production, use of hybrid drip irrigation, and the use of alternative agricultural technology. For example, the state of Montana currently supports 40 breweries that consume 2.7 million kilograms of craft malted grain half of which is produced in the state of Montana (Montana Brewers Association, 2013). Opportunity may exist in niche agricultural markets such as drought tolerant varieties of hops and barley to support the growing craft beer industry in the Southern Rocky Mountain Region. The pre-WW II acequia community was resilient in that the farmers promoted crop diversity, utilized low energy inputs from farm machinery, and maintained sustainable practices on small parcel farms. Overall, land use conditions in Alcalde have been altered, but the acequia infrastructure and farm plot arrangements have endured and have adapted over time, indicators of resilience with flexibility to transform and meet climatic and other challenges in the future.

### 3.3 Economic trends and adaptation opportunities

As communities confront challenges and stressors from population, environmental and economic changes the community capacity for resilience, preparedness and adaptation depends not only on the rate and intensity of stressor changes but also importantly on accumulations of various types of capital assets including human, financial, resource, and social-cultural. Viewed as “storages” or “reservoirs”, these capital assets act broadly as indicators of community wealth and strength, representing a type of community “balance sheet”.





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Affected positively or negatively over time each asset category is strengthened or diminished by changes in the status or performance of a community's economic, demographic and environmental systems. For example, changes in regional net income from employment and productivity will either increase or decrease the community's aggregate financial wealth (leaving aside for now issues of distribution and equity). Another example can further illustrate. Natural and environmental resources, including fertile agricultural crop, grazing and forest lands and water resources, are seen as contributing to the essential character of an acequia community. Many of these resource assets are renewable and their quantity and quality are subject to fluctuation and change depending on variable factors such as climate and natural events and cycles, rates of extraction and transformation including conversion of agricultural land to development, and changes in regulatory policy that can erode or strengthen the asset value by affecting resource access and use.

Recent survey results (Mayagoitia et al., 2012) show that acequia residents identify closely with land, water, and community resources and that this perceived connectivity is one of the strongest factors among those considered for contributing to the community's adaptive capacity, preparedness and resilience. As seen in Fig. 13, this view is particularly strong in the acequia communities along the Rio Hondo where "a spirit of cooperation" and "equity in water sharing" were equally strong in association with adaptive capacity and strength.

The concept of a community balance-sheet also conforms well to notions of sustainable development such as it was defined by the Brundtland Commission that "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Therefore, long-run sustainability and resiliency would be consistent with a community's overall 'balance sheet' that remained healthy and resistive to excessive degradation and long-run net loss. Although reductions in non-renewable resource capital are expected, it would also be consistent to expect an associated accretion in economic capital as a result of the transformation of natural capital into economic capital. For example, for a mining





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community to remain economically viable over the long-run as mineral resources are depleted, its economy must invest in transitional economic development. Otherwise, it would risk long-run economic decline and consequential losses and erosion in the other categories of community capital including population and sociocultural resources. In some cases, an exception could be some restoration of renewable environmental capital e.g., wildlife, wildlands, as population stresses are reduced.

Over the last forty years there has been a steady transformation of the employment base for the communities in the two counties in Northern New Mexico with the largest concentrations of acequia communities, Taos and Rio Arriba Counties. As Fig. 14 shows, these communities are both transforming from primary extractive and resource-based economies to service, professional and government-service centered economies. While employment in the primary sectors remains relatively constant, except for mining which has fallen slightly, all the growth has been focused in professional and service sectors. Between the years 1970 and 2000 the services sector shares have risen from about 50 to nearly 70 % in Taos County, and similarly in Rio Arriba Country from about 40 to over 50 %. Agricultural employment has remained relatively flat through 2000 (the last year data were available) with employment shares approximately 4.0 and 8 % for Taos and Rio Arriba, respectively. These trends seem to suggest both a greater dependence on regional employment centers, greater off-farm income support, and higher commuting rates. Such regionalization can affect community "balance-sheets" in several, sometimes offsetting ways. For example, diversification from traditional extractive economic activities can strengthen incomes and raise financial wealth and capacity, although perhaps at some cost to sociocultural strength and well-being with less time and commitment to community-centered activities and relationships.

Trends and changes in farm income and the agricultural economy of the acequia region coupled with changes and variations in the water supply situation over the last forty years are shown in Fig. 15. Roughly consistent with the long-run steady employment picture in farming and ranching, there does not appear to be a strong





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positive or negative trend in farm and ranch incomes over this period. However, there is a relatively high degree of income variability that is largely independent of regional water supply conditions. This suggests that other economic or perhaps productive factors are contributing to income variability more than water supply conditions. This does not necessarily imply that farm and ranch operations are insensitive to surface-water supplies and conditions, perhaps just that the adaptations and coping strategies are available to mitigate streamflow variability – at least in the aggregate across the counties and all the agricultural sectors. This is possibly good news that the capacity to withstand variations in water supply and streamflow – at least within the recent range of experience – is not particularly threatening to the agricultural livelihoods. However, persistent and intense drought conditions, like those suggested by some climate change scenarios may push the system beyond current capabilities and capacities.

## 4 Sociocultural perspectives to understand resilience

Traditional local knowledge about the hydrosocial cycle of acequia operations is a key factor in acequia resilience. When irrigators are confronted with unexpected disturbances or changing climate that affects water supply, they adapt specific practices while maintaining community cohesion. We use sociocultural values and crop yield considerations to illustrate our ongoing work to quantify the multiple disciplinary components of these systems, and translate them into a common language of causal loop diagrams.

### 4.1 Sociocultural knowledge and the hydrosocial cycle

In the acequia culture of the historic Rio Arriba bioregion (northern Rio Grande), attachment to place runs deep among the multiple generations of irrigators who have been rooted in the land. They have eked out an existence mostly at subsistence levels despite the harsh conditions in semiarid uplands susceptible to the unpredictability





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of climate, pressures of modernization, and a fundamental change from a traditional pastoral economy to wage-based, off-farm employment after WW II. Starting in 1598, caravans of hispano settlers and Mexican Indian allies came up the Camino Real from Mexico City, traversed the Jornada del Muerto north of El Paso del Norte, and finally reached the confluence of the Rio Grande del Norte and the Rio de Chama. Here, they set out to establish agricultural colonies in this northern frontier of New Spain in search for perennial streams of water fed by distant snow packs in the alpine sierras to the north. The colonists knew that in a desert environment, there could be no irrigation without a snowpack, a natural system reservoir that accumulates and holds water during the winter months until the rising temperatures release spring run-off needed to water crops and fields in the valley bottomlands.

As the first public works projects, the settlers diverted streams by constructing *presas*, diversion dams, and then hand dug irrigation canals, acequias, on one or both banks, all without the benefit of modern surveying equipment. These engineering works were of local physical design in order to operate as gravity flow systems following the contours of the land with the goal of extending the boundaries of irrigation to the maximum extent before returning the canal back to the river. Due to variations in local topography, the design of each ditch system was unique, always tailored to local conditions and natural features in the landscape. This human engineering design, coupled with its associated social configuration, was specifically located and embedded in the hydrological system. Acequias diverted and used surface water only when available and therefore made periodic adjustments dependent on water supply stored as snow pack in the upper watershed. Water management practices and operating procedures were adopted in response to natural system conditions during spring run-off, season to season, and over time these repeated adjustments produced a distinctive, community-based hydrosocial cycle.

Of necessity, and key to the success of each system, the community of irrigators did not adhere to a prescribed set of regulations from a central authority, and instead they negotiated institutional arrangements among the collective that they called *arreglos*,





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operational rules that were specific to the water delivery requirements of the shared canal and its laterals. The taking of water by a collective enterprise during the initial *saca de agua* carried forward into the local customs and traditions for water distribution and the operations and maintenance of the irrigation works including repairs when needed at the diversion structure in the river and the annual rituals of ditch cleaning during the early spring just before the expected run-off season. This self-organized enterprise wedded the irrigators into a community system of water management that bonded them and formed a hydraulic society, a culture of water based on shared norms and mutualism. Rules for sharing such as *repartimiento* evolved into a set of customary practices based on knowledge of the land, watershed, and water supply variability.

As with other forms of traditional agriculture around the world, acequia irrigation in the Rio Arriba is knowledge intensive in terms of understanding and responding to the local hydrological and environmental conditions upon which the system depends. Traditional agricultural systems are knowledge intensive, and the complete system is carried collectively in the local knowledge of the irrigators, particularly with regard to the distinctive micro-region of their community: soils, climate conditions, crops, and water requirements for every niche suitable for agriculture (Glick, 2006). The mutuality of the irrigators derives from the values encoded in the operational rules of water sharing, namely, equity, justice, and local control (Maass, 1986). This knowledge is derived from and expressed in practical, experiential terms and after repeated cycles is embedded in the culture and passed on to new generations as part of the social and institutional memory of the community (Folke et al., 2003).

### 4.2 Acequia resilience: survey data and findings

In 2008 the New Mexico Acequia Association (NMAA) conducted an assessment survey to document the concerns of its membership in order to generate effective governance program planning and strategies for the benefit of acequias. Topic areas included needs, crop and water management trends, infrastructure conditions, and overall health of acequias. A synopsis report by the NMAA highlighted the survey





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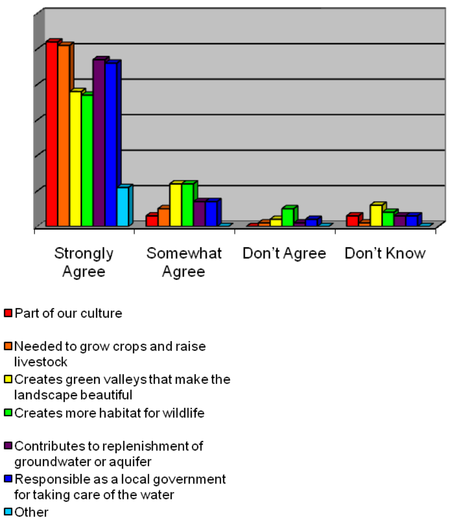
responses as in the two example charts below. The results show that the cited values are of high importance and community participation, lack of irrigation, and infrastructure issues were of main concern (see charts below).

*What is your opinion about the following statements about the importance of your acequia to your community?*





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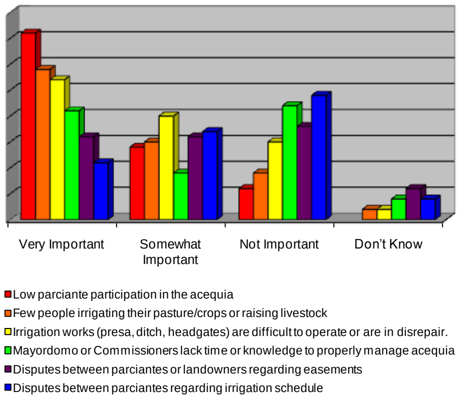
*What do you believe are the important challenges within your acequia?*




### 4.3 Acequia resilience focus group data

Traditional local knowledge about the hydrosocial cycle of acequia operations is a key factor in acequia resilience when the irrigators are confronted with disturbances, unexpected events, or changing climate that affects water supply. Adaptability in times of stressors is self-evident by the fact that acequias of the Rio Arriba as human and social institutions still operate and have not disappeared even after political administration under four sovereigns and their shifting water law regimes: Spanish colonial, Mexican Period, US Territorial, and New Mexico statehood in 1912. Focus group sessions with acequia officials and *parciantes*, along with supporting evidence from similar case studies in other arid regions of the world, suggest a number of intriguing propositions with regard to resiliency factors of acequia irrigation systems:

1. Attachment to land and place develop a collective identity with a set of shared values and cultural norms, producing what can be called an "acequia imaginary";

2. Mutual networks and social density result in cohesion and solidarity of community when confronted with change or stressors from outside the community;

3. Leadership by key individuals such as the mayordomo and the commissioners maintains and retains the customary rules and local management practices of the system;

4. Social memory embedded in the culture instructs acequia leaders and *parciantes* on how to respond to and withstand disturbances or year to year changes;

5. Ecological knowledge of local conditions and environment is carried collectively and transmitted to new generations;

6. Local control of resources increases the capacity to adapt in times of scarcity such as cycles of prolonged drought;

7. Autonomy of decision making structure and discretionary authority permit rapid adjustments in operational rules and practices when warranted by changing or unexpected conditions.

Information gathered from the local communities was placed into the framework of a causal loop diagram. The causal loop diagram is a tool to represent interacting variables of a system, and it is a precursor to simulation modeling. The sociocultural causal loop diagram is displayed in Fig. 16. Causal loops were also created for hydrology, economic, and environmental variables as discussed in Fernald et al. (2012). Community members were invited to a workshop with researchers to refine the causal loop diagrams based on their own understanding. The data that researchers collected were to identify and assess the key variables among all of those identified in a collaborative community water research process (Guldan et al., 2013).





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## 5 Discussion: identifying essential variables to model future scenarios

Ongoing system dynamics modeling based on the causal loop diagrams will be used to turn narratives into future scenarios that identify thresholds and tipping points of sustainability. Our ongoing approach is to distill out the essential variables in the system using our field data from the multiple disciplines and incorporate them into a simulation model. When we put together the causal loop diagrams for all disciplines and work with community members, key variables emerge as shown in the essential causal loop diagram (Fig. 17).

To illustrate our modeling approach that will extend to all disciplines, we present here a theoretical example for model development showing interacting prices, crops, and water use. Figure 17 shows a number of variables. We select two here, Cultivated Acreage and Crop Yield that relate closely to crop production (irrigated agriculture) for the Acequia de Alcalde, an acequia along the main stem of the Rio Grande. Each of these two variables is affected by more variables than the "overall" causal loop diagram indicates (see Fernald et al., 2012), for example labor availability, crop price, and market. Perennial forages and tree fruit orchards are the two primary, yet very different, crop types that make up the majority of the irrigated land the Acequia de Alcalde provides water for. Currently, there are on the order of 50 acres of tree fruit orchards and 620 acres of hay forage (Table 2).

The proportion of irrigated acres in orchards vs. forage crops can potentially be influenced by changes to various factors/drivers. Decrease in availability of farm labor could lead to a decline in orchard acres, whereas an increased demand for local fresh food might convert some forage fields into orchards. Climate change may exacerbate the common problem of tree fruit crop loss due to late spring frosts. As has been the trend, any factor that decreases acreage of orchard crops may increase forage acreage or result in less overall cultivated acres.

A scenario of decreased irrigation water supply, such as with a long-term drought, might shift acres from forages to apples or other specialty or higher value crops that can more easily be adapted to micro-sprinkler or drip irrigation (a difficult resilience strategy for producers only having equipment and experience with forage crops). Forage producers might also shift to forages that use less water, but that would also yield less. Or, a loss in overall cultivated acres may occur as hay fields are left idle.

Cropping patterns could also change due to socioeconomic, policy, and cultural factors, in extreme cases having an effect on the hydrology of the system. For example, grazing restrictions or increased costs of grazing permits in uplands due to policy changes could impact local demand for hay: an increase in demand could occur to meet herd feed needs; or, a decrease in demand could occur if herds are reduced, possibly leading to a shift to other crops or idling of acres. The latter could reduce aquifer recharge and groundwater return flow to the river due to lack of seepage and deep percolation (Fernald et al., 2010).

Along many acequias, demand for housing and the associated increase in land prices have often caused pressure to subdivide fields into residential lots. This decrease in irrigated acres has likely reduced seepage and percolation in the system and thus reduced aquifer recharge and groundwater return flow. In the case of one county (Rio Arriba), a resilient response to this has been an ordinance passed several years ago that stipulates agricultural fields be developed in a manner that maintains 70 % as open field, with 30 % allowed for development as cluster housing (Rio Arriba Agricultural Protection and Enhancement Ordinance; adopted on 31 January 2002; prepared by the Rio Arriba County Planning and Zoning Department, Rio Arriba County).

In order to identify resilience, sustainability, thresholds, tipping points, and future directions for hydrologic and community health, our ongoing work is developing a model that brings together all scenarios to help identify higher levels of interaction than are obtainable with disciplinary approaches. We will use crosscutting scenarios within system dynamics modeling to test tipping point hypotheses. System dynamics modeling uses stocks of key variables and parameterized flows between them to recreate the systems under consideration. In our case, we will bring together the





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multiple threads and model scenarios based on our field data from the multiple disciplines.

This approach enables a quantification of system connections as illustrated by the grazing example. A preliminary analysis of farmer/rancher surveys and historical records of public land grazing in areas adjoining irrigated valley study sites, suggests a tight connection between irrigated hay production and year-to-year variation in upland livestock numbers (S. Lopez, unpublished data). Although it is difficult to isolate the influence of hay production from factors such as public land use policies that determine the length of the summer grazing season (and, therefore, the number of winter feeding days), availability of valley-grown forages appears to be an important driver of livestock herd dynamics in the local farming/ranching communities (S. Lopez, unpublished data). Thus, projected changes in snowmelt regimes and irrigation water availability could indirectly affect traditional livestock-raising activities and weaken local economies and ancestral valley-upland sociocultural connections.

We have identified resilience as well as susceptibility to change. We will construct future scenarios that test the limits of these systems. We can imagine an interacting causal model based on our causal loop diagrams and field evidence that sheds light on the tipping point hypothesis. What will happen, for example, if acequia farmers sell their land, and water is transferred off the land to regional urban centers? Based on the integrated model, we might find that under this scenario farming is reduced impacting the timing and distribution of flow, reducing seepage and groundwater return flow, reducing riparian function, and reducing river flow in late summer and fall. Reduced farming and grazing results in changing vegetation structure and increased density and cover, which leads to increased wildfire in a warmer future that further exacerbates pressures on grazing and farming. We have shown that these systems adapt and change, but there are also signs that key components of the acequia systems have limits to resilience.





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## 6 Conclusions

Keys to resilience are found in hydrological and human system connections. Seepage from acequia systems supports a host of hydrologic and riparian resilience functions. Hydrologically, seepage recharges groundwater and provides attenuated return flow to rivers and streams. Riparian areas support most of the biodiversity in these regions. Reduction in water may reduce riparian areas and acequias can provide additional refugia in times of low water. Community cohesion has resilience in the value of attachment to place derived from acequia and local farming culture. Livestock-raising contributes to strengthening the economic and social resilience of traditional acequia irrigation communities of northern New Mexico. Ability to grow irrigated forages appears to be critical to the persistence of this well established agricultural activity. Changes in snowmelt regime and water availability for irrigation could cause further reductions in herd numbers and severely weaken the cohesion of acequia farming communities.

Acequias are resilient because they are in step with the scope and scale of variability in the natural systems. The roots of sustainability are the intricate ties that have been crafted over generations linking human and hydrological systems. For example, acequia water is distributed in keeping with the highly variable precipitation of the region. Unlike priority water law that gives the oldest water rights the water in times of scarcity, acequias share the water. In wet times everyone gets more, and in dry times everyone gets less. Irrigated lands were established to match the wet and dry years, with vital lands near the river irrigated in dry years, and lands farther from the river added to the irrigated footprint in wet years. Adaptation to semiarid system variability and the connection to place are at the heart of acequias' ability to adapt.

Our study has demonstrated that acequia systems have remarkable resilience and adaptive capacity, but also show susceptibility to major upheaval. Thus shocks to the system such as climate change and land use change that impact water and ties to the land are particularly disruptive. Tipping points may be reached when external drivers push these systems beyond their historic limits. It is widely acknowledged





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that regional megadrought in what is now the US southwest pushed Pueblo peoples beyond their capacity to adapt and set up widespread migration and cultural upheaval. Signs of tipping points are showing now in the Taos valley where developers have paved over acequias blocking downstream users access to water. In 2013 after 10 yr of drought, river water was significantly too low, and acequia communities were on the verge of filing lawsuits against upstream users until seasonal monsoon rains allowed irrigation to resume. Resilience and tipping points can be propagated both upstream and downstream due to hydrologic connections and trans-basin water movement. Fortunately it rained in 2013, but if droughts of historic depth and duration occur, acequia systems appear vulnerable to upheaval.

*Acknowledgements.* This study was funded in part by the New Mexico Agricultural Experiment Station and National Science Foundation grants #814449 New Mexico EPSCoR, and #1010516 Dynamics of Coupled Natural and Human Systems.

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**Table 1.** Agricultural change in Alcalde, NM.

| Alcalde | 1935 | 1959 | 2011 |
|---|---|---|---|
| Population | | | |
| Total Land in Study Area, acres | 326.2 | NA | 343.9 |
| Total Bosque, acres | 129.3 | NA | 144.2 |
| Bosque on Private Land, acres | 8.9 | NA | 1.3 |
| Agricultural Zone, acres | 196.8 | NA | 199.7 |
| Agriculture | 107.3 | NA | 47.7 |
| Agriculture – FC | 84.5 | NA | 30.0 |
| Agriculture – Fallow | 2.8 | NA | 8.9 |
| Agriculture – Orchard | 2.1 | NA | 6.5 |
| Developed Land, acres | NA | NA | 42.3 |
| Unused Land, acres | NA | NA | 64.2 |
| Total Area of Buildings, acres | NA | NA | 24.0 |
| Total Area of Buildings in Ag Zone, acres | NA | NA | 8.3 |
| Number Tracts | 56 | NA | 107 |
| Minimum Tract Size, acres | 0.1 | NA | 0.3 |
| Maximum Tract Size, acres | 14.8 | NA | 18.7 |
| Average Tract Size, acres | 3.6 | NA | 1.9 |
| Median Tract Size, acres | 2.2 | NA | 1.1 |





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**Table 2.** Approximate cultivated acreages (D. Archuleta, personal communication, 2012), and yield and gross revenue ranges (Forage, Currier et al., 1995, and Lauriault et al., 2004; Apple/Orchard crops, S. Yao, personal communication, 2012) of two crops, and potential effects from various factors (Acequia de Alcalde).

| Cultivated Area | × | Yield/area | = | Total Yield | Gross Revenue |
|---|---|---|---|---|---|
| Forage 620 acres | | 4–6 tons/acre | | 2500–3700 tons | USD 0.5–1 million |
| Apple/Orchard crops 50 acres | | 6–13 tons/acre | | 300–650 tons | USD 0.3–0.65 million* |

* Through direct marketing at roadside stands or farmers markets, apples and other orchard crops can potentially produce significantly higher revenues per acre than indicated.





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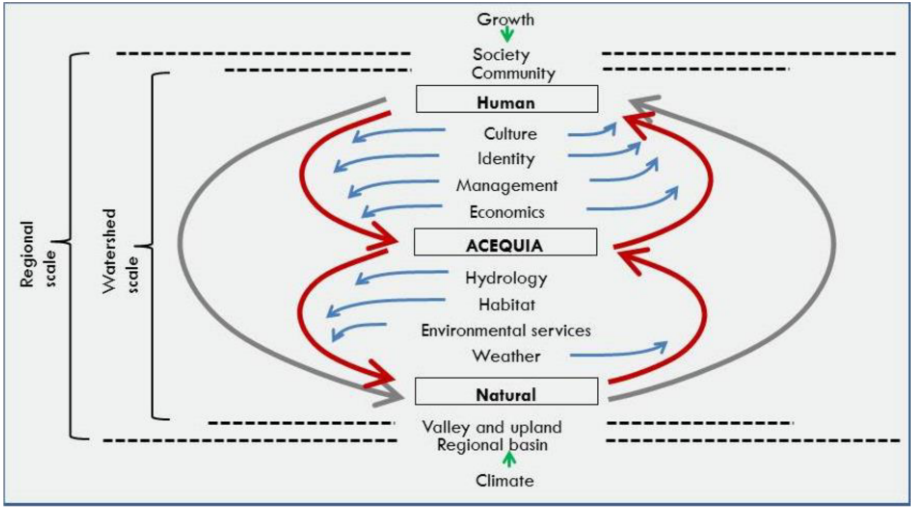


**Fig. 1.** Acequia-irrigation centered connections of human and natural systems (Fernald et al., 2012).





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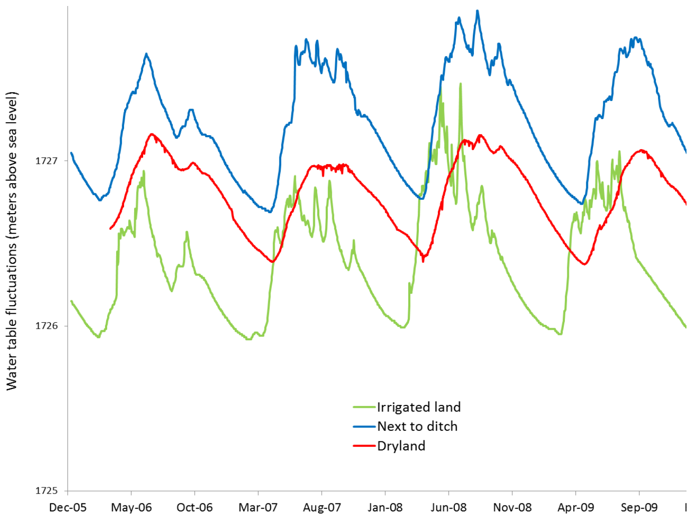


**Fig. 2.** Seasonal water table fluctuations in response to irrigation inputs in one transect of wells in an acequia-irrigated agricultural valley in northern New Mexico.





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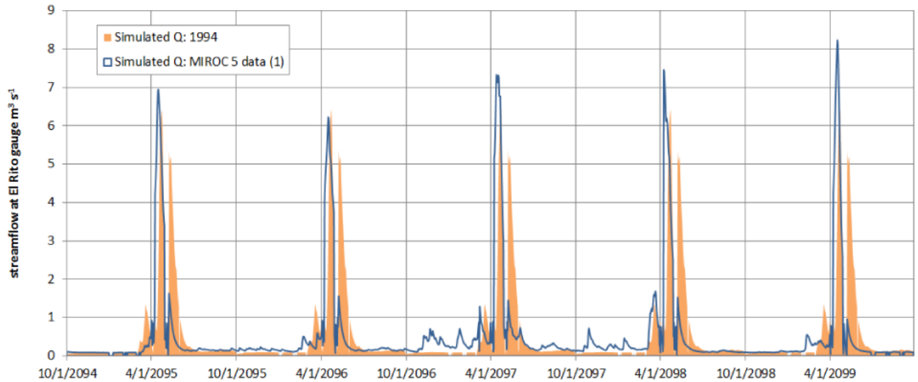


**Fig. 3.** Runoff simulated for the El Rito watershed showing average runoff in 1994 and earlier runoff with higher peak flow in a warmer modeled period 2095–2099.



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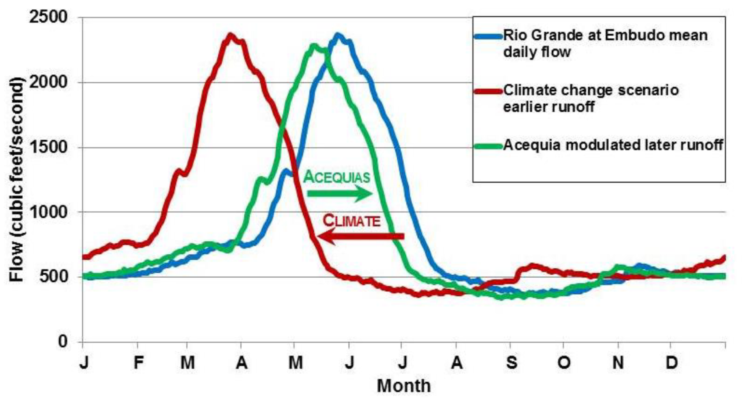


**Fig. 4.** At regional scale, acequia surface water groundwater interactions may ameliorate effects of climate change by delaying spring runoff that is projected to be earlier in the year.





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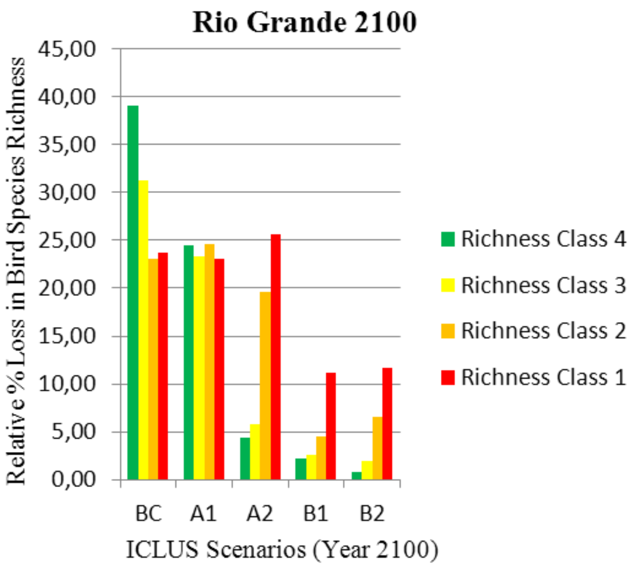


**Fig. 5.** Relative percent loss of bird habitat for four species richness classes (1-low, 2-low-moderate, 3-moderate-high, and 4-high).





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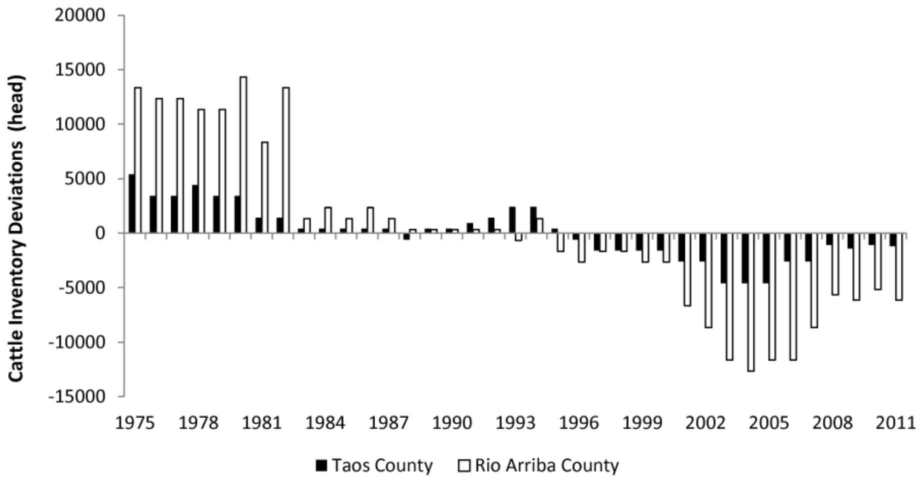


**Fig. 6.** Annual deviation from estimated cattle long term (35 yr) mean inventory for Rio Arriba (31 662 head) and Taos (8597 head) Counties in northern New Mexico (Data NASS, 2012).





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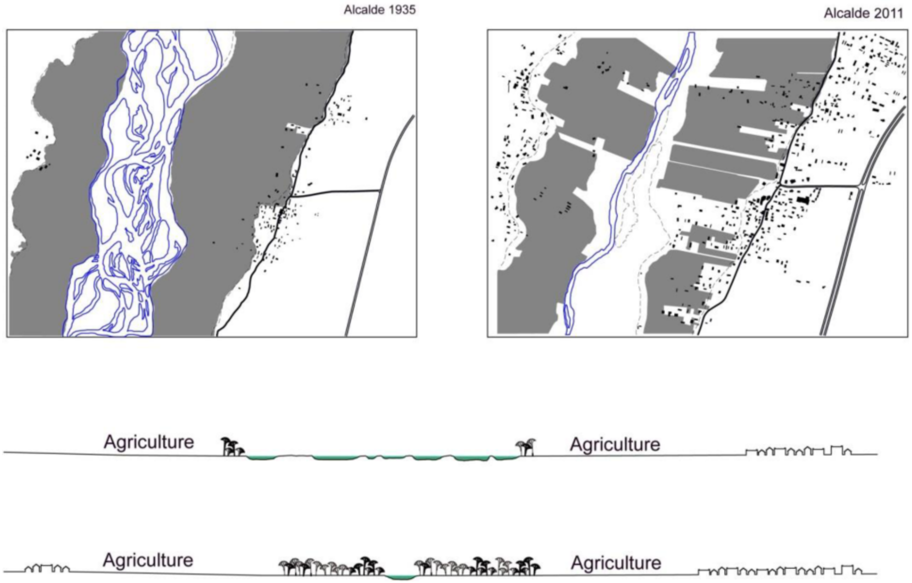


**Fig. 7.** Alcalde landscape morphology.





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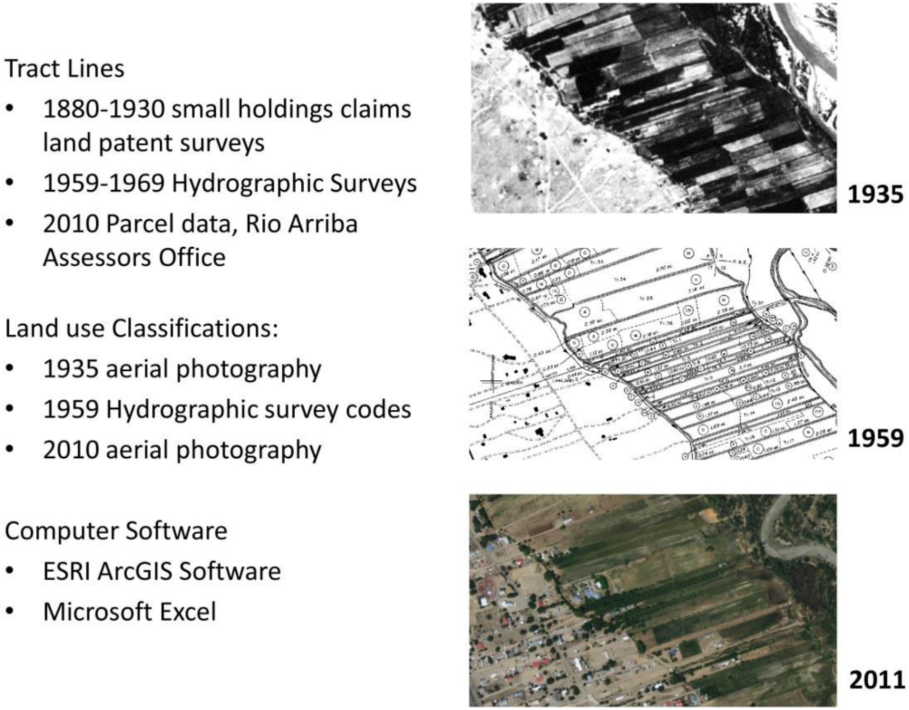


**Fig. 8.** Methodology for mapping land use change.





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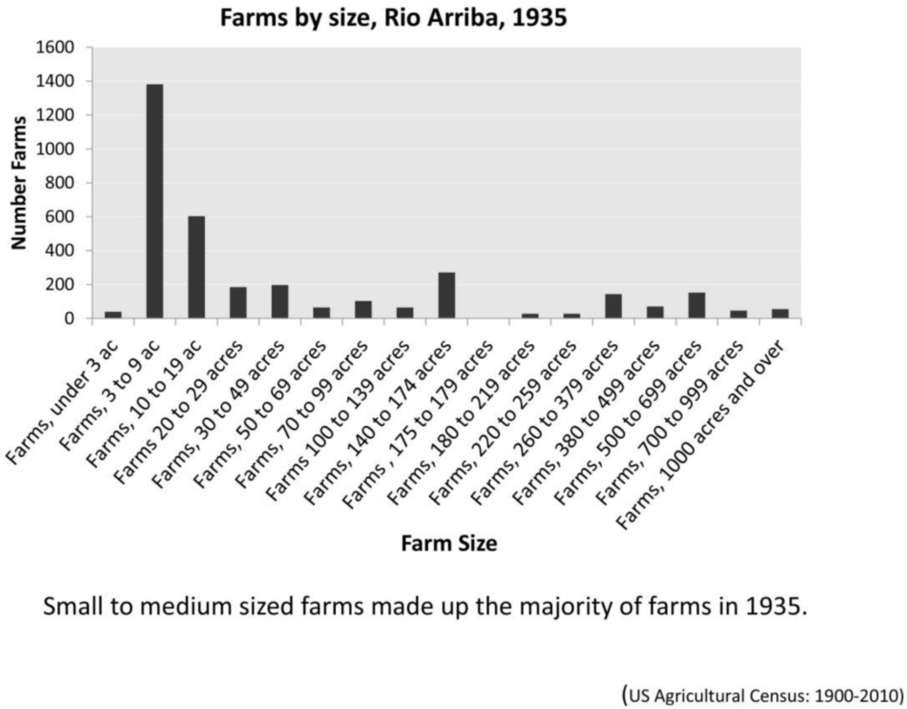


**Fig. 9.** 1935 agricultural parcel size Rio Arriba County.





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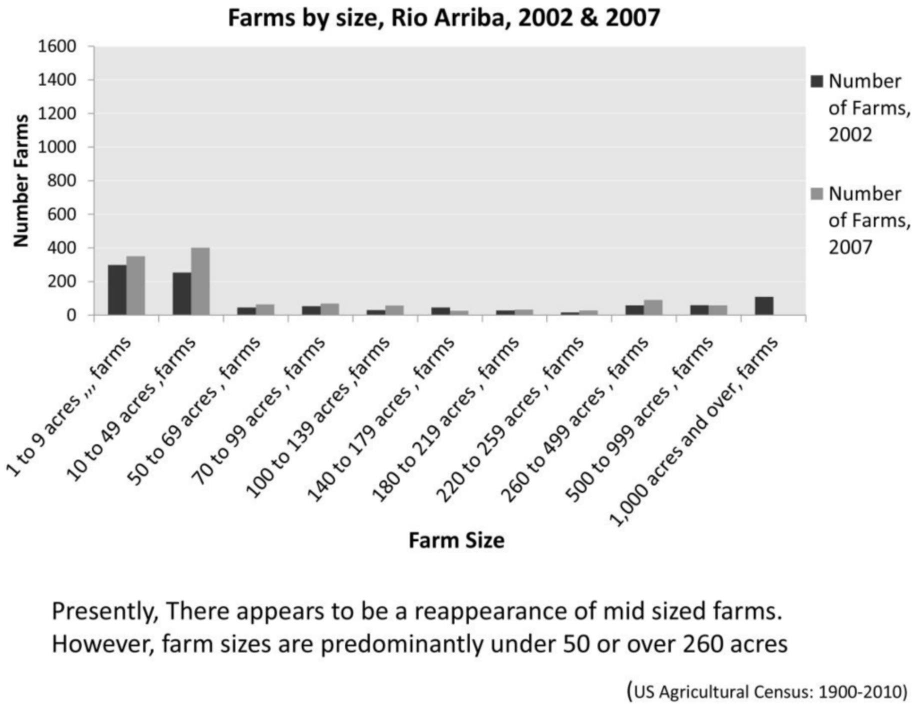


**Fig. 10.** 2007 agricultural parcel size Rio Arriba County.

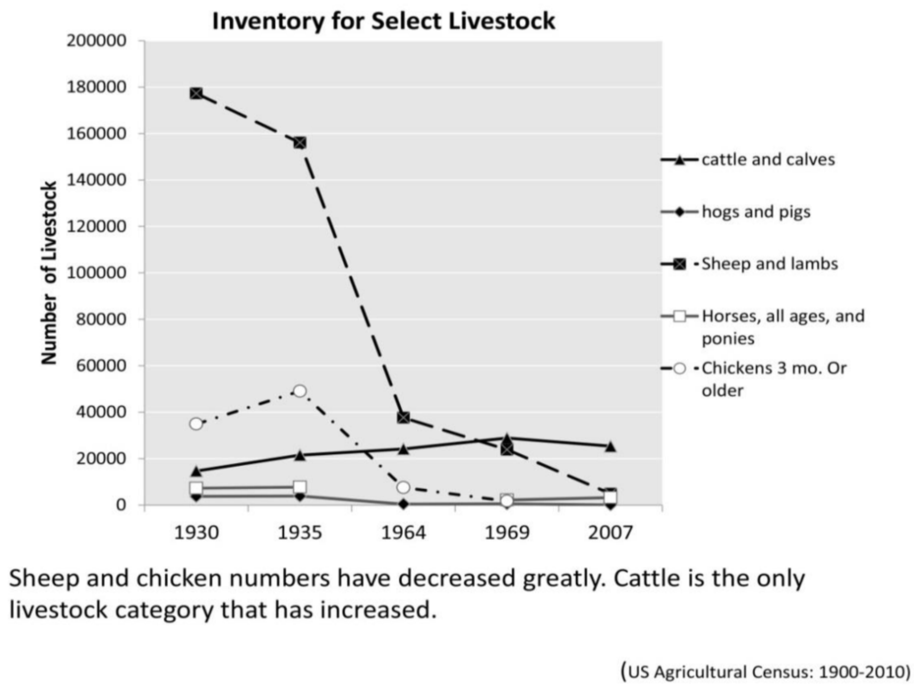


**Fig. 11.** Inventory of livestock 1930–2007, Rio Arriba County.





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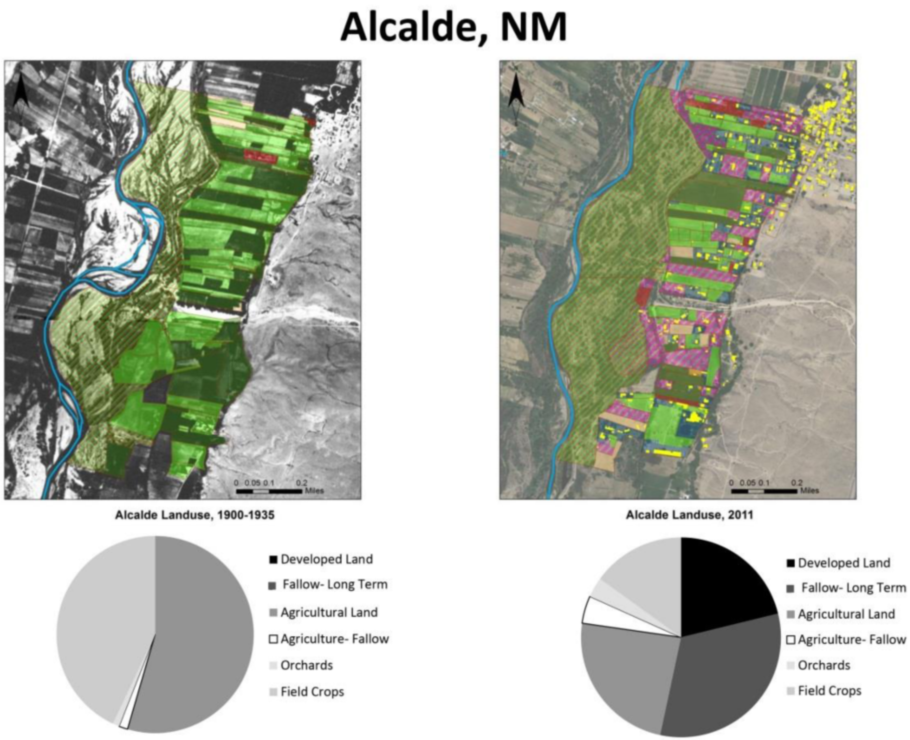


**Fig. 12.** Alcalde agricultural tracts 1935–2011.





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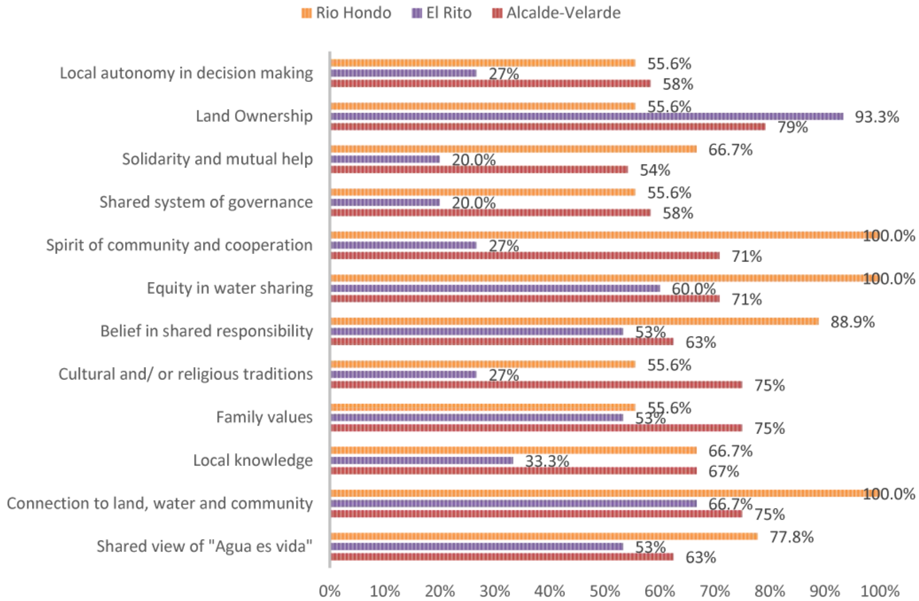


**Fig. 13.** Acequia characteristics perceived to "best contribute" to acequia adaptive capacity, past adaption and resilience.



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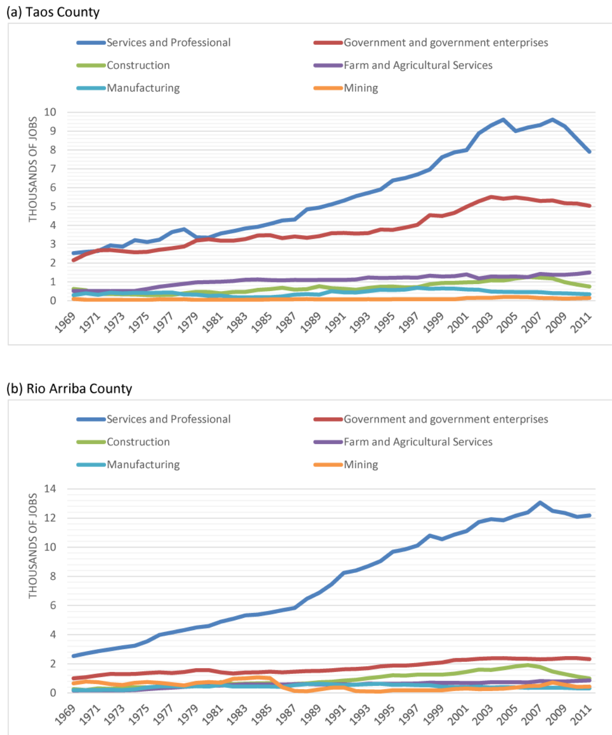


**Fig. 14.** Employment shares and trends by sector in Taos and Rio Arriba Counties, New Mexico. Sources: U.S. Bureau of Economic Analysis (2013b).





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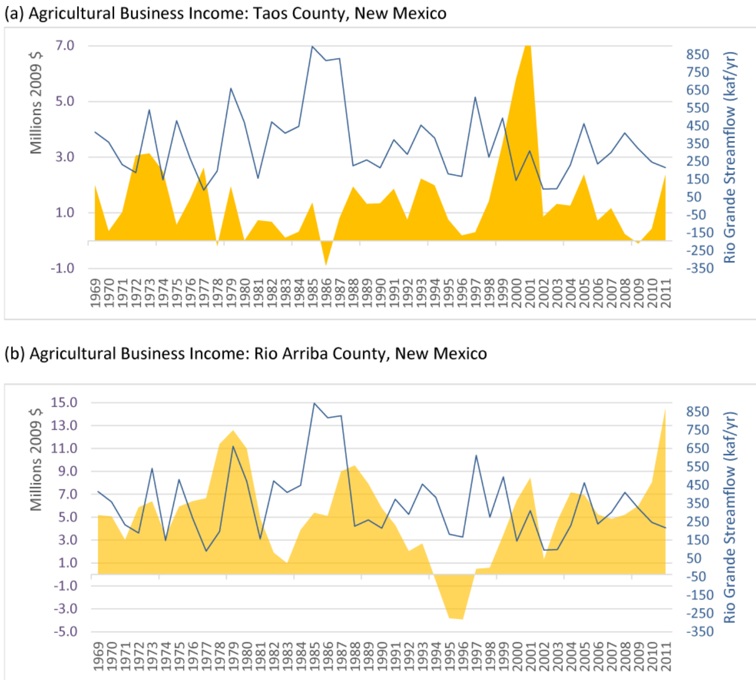


**Fig. 15.** Trends and changes in agricultural incomes (orange areas) and streamflow (blue lines) for Taos and Rio Arriba Counties in New Mexico. Sources: U.S. Bureau of Economic Analysis (2013a) and USGS (2013).





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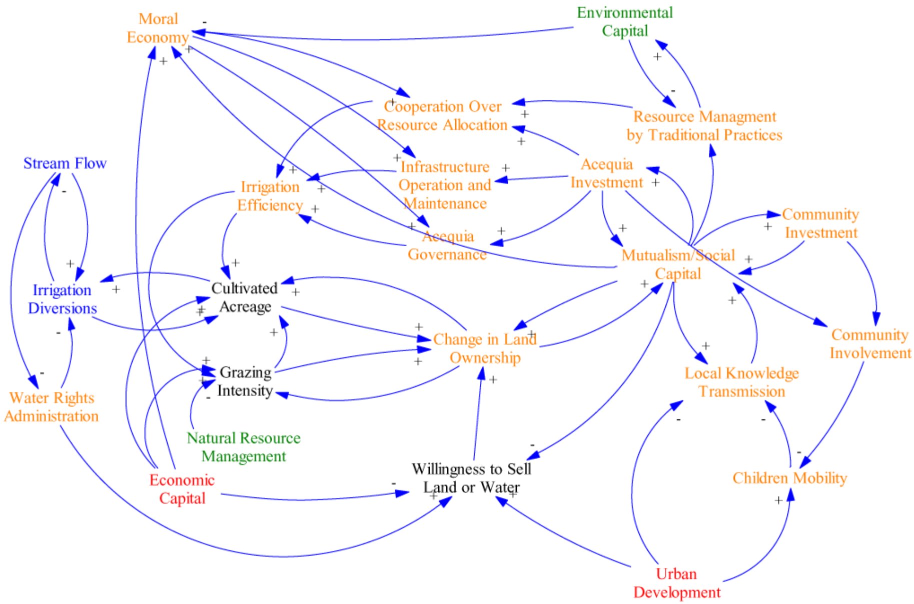


**Fig. 16.** Sociocultural subsystem causal loop diagram. Orange colored variables are primary to the sociocultural subsystem and other colors are primary to other subsystems (blue are hydrology, green are ecosystem, and red are land use/economics). Black are critical variables integrating across multiple subsystems (Fernald et al., 2012).

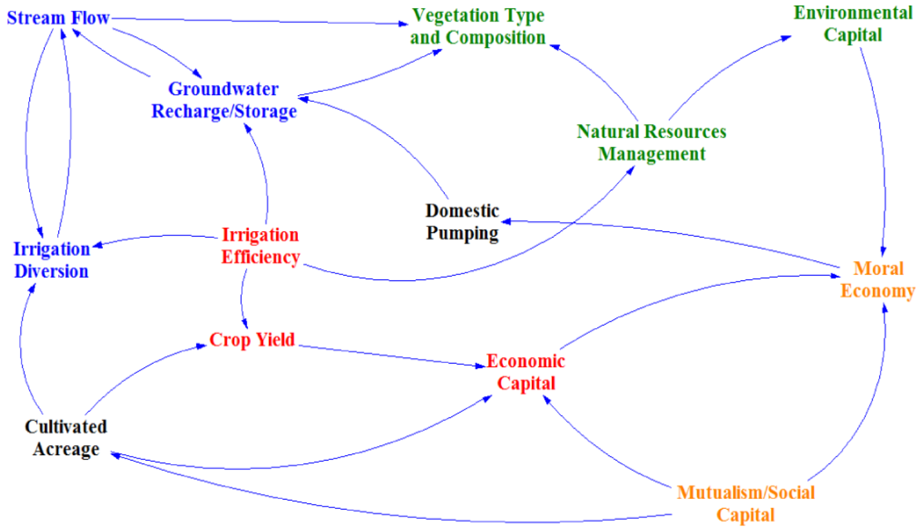


**Fig. 17.** Essential causal loop diagram with key variables for modeling. Black variables are critical elements integrating across multiple subsystems, while colors are primary to individual disciplines.





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