Robustness and vulnerability of community irrigation systems: the case of the Taos valley acequias

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August 2009

Abstract

Traditional economic and policy analysis theory has emphasized the implementation of private or public property rights regimes in order to sustainably manage natural resources. More recent work has challenged this approach by examining the strengths and weakness of communities of users who frequently manage such resources. This paper contributes to this literature by analyzing the acequia irrigation communities in northern New Mexico. Through statistical analysis the paper finds that the acequias' ability to maintain a critical performance function, crop production, is aided by water sharing agreements and access to groundwater, and that it is hampered by property rights fragmentation and urbanization.

Keywords: Common-pool resources**,** Social-ecological systems**,** Acequias**,** Irrigation**,** Robustness
JEL Classification: Q15; Q25

1. Introduction

Traditional economic theory and policy analyses have long forecast the destruction or exhaustion of common-pool resources, such as forests and fisheries, unless they are governed by an external authority that is capable of imposing an idealized private or public property-rights system on those who use the resource [12, 13]. As scholars have begun questioning these assumptions, attention has turned to exploring the conditions under which groups of users can successfully manage a resource using common property rights systems [1, 10, 22].

Irrigation systems are one example of a common-pool resource that is managed by decentralized user groups in many regions around the world. The presence of long-lasting, decentralized irrigation systems has created several puzzles [20, 27]. First, how do such communities resolve collective-action problems inherent in managing irrigation systems over time? Second, how have their organizational adaptations to past disturbances affected their abilities to adapt to novel disturbances in an increasingly interconnected world? Given the abundance of community-based natural resource management systems around the world and the incidence of novel disturbances upon them, answering such questions has practical importance for the management of many natural resources. Additionally, the lessons learned from studying one property rights regime, in this case common property, can potentially be applied to alternative regimes that interact with similarly complex natural resource systems.

This paper addresses these questions by analyzing 51 acequia irrigation communities in Taos valley of northern New Mexico as a social-ecological system. To analyze such systems, both the social system and its biophysical environment need to be addressed in order to understand how the linkages between them produce important outcomes. Unfortunately, a gap exists in the literature on human-environment interactions at precisely this intersection, illustrating the difficulty in conducting analyses that involve both social and environmental variables. This paper addresses this gap using a variety of methodologies and data sources to study the acequias. On-site in-depth interviews and content analysis of historical documentation were conducted, and remote sensing imagery with geographic information systems were employed to generate data that would allow for regression analysis.

This research was conducted to test the following set of hypotheses. These hypotheses are of two types: first, hypotheses H1, H4, H5, and H6 each relate a particular feature of an acequia to its robustness to droughts, which the acequias have periodically experienced their entire time in Taos. Second, H2 and H3 stipulate that the acequias are not robust to two novel disturbance types. Robustness here is the ability to maintain an important performance metric in the face of disturbances, operationalized here as the maintenance of crop production over time. In acequias with favorable characteristics, such as water sharing agreements or small group size, we expect higher levels of crop production per unit area over time as various disturbances occur. In acequias facing greater levels of disturbances they are vulnerable to, we expect lower levels of crop production. The hypotheses are listed here:

H1: Robustness to droughts increases as the number of members in an acequia decreases.

H2: The acequias are vulnerable to the fragmentation of land rights.

H3: The acequias are vulnerable to urbanization.

H4: Access to groundwater as an alternative water source increases acequias' robustness to droughts.

H5: Water sharing agreements increase acequias' robustness to droughts.

H6: Soils with high water retention in a dry environment increase the robustness of the acequias to droughts.

The reasons for each of the hypotheses are explored in more detail in the following section. H1 is drawn from the literature on community-based CPR management. H2 and H3 are drawn from observations and interviews with farmers in the study area, and negative outcomes that have resulted from the processes of land fragmentation and urbanization in other parts of New Mexico. H4 is drawn from previous hydrological work on the acequias. H5 is based on descriptions of water agreements by interviewees and historical testimonies, as well as an analysis of the Kangra irrigation systems of Kuhl in northern India, which arrived at a similar conclusion [5]. Finally, regarding H6, soil properties are included in order to statistically control for the effects that various soil properties have on local water availability.

The main findings of this study are: (1) The acequias are vulnerable to the disturbances of urbanization and the fragmentation of land property rights; (2) The availability of alternative sources of water via groundwater and water sharing agreements increase the robustness of the acequias to droughts; and (3) acequias of small-to-medium size are more robust than larger acequias.

2. Background

2.1. Common-pool Resource management and collective action

An Irrigation system is an example of a common-pool resources (CPR) which is finite, exhaustible, and which incurs high costs of exclusion to limit the intensity of resource use. These characteristics of CPRs lead to at least two types of collective-action problems: those of resource appropriation and provision [23]. Collective-action problems are a dilemma for user communities due to a divergence between individual and community-level interests. In these situations, the pursuit of individual gain is collectively harmful, and it can be difficult for users to self-organize and act collectively in pursuit of common interests. It is this condition that has historically convinced many scholars and policymakers of need to impose private or public property regimes to manage CPRs instead of communities.

An appropriation problem can result in the overconsumption of an exhaustible resource, such as water, when an individual benefits from personal consumption at the expense of the community and the condition of the resource. This is a special case of negative externalities, and is reflected in the commonly observed upstream-downstream relationship between irrigators that pervades irrigation systems. A provision problem, or public good problem, can result in underprovision of the infrastructure needed to appropriate a resource, such as an irrigation headworks. This is essentially a positive externality which occurs because it is difficult to exclude non-contributors from benefiting from, or free-riding on, the efforts of contributors. Individuals may then enjoy the benefits of others' provision without contributing, which lowers their incentive to contribute themselves, leading to socially sub-optimal levels of provision.

Much of the literature on CPR management has focused on common property regimes, where individuals' rights to the resource are contingent upon their continual adherence to community rules and norms. A variety of factors have been hypothesized and tested to contribute to the robustness of cooperation among users facing the social dilemmas posed by CPRs [1, 22, 23]. These include: (1) institutional arrangements and property rights systems; (2) characteristics of the user groups such as their size or heterogeneity; (3) levels of social or economic connectivity within and between user groups or between them and external political and economic environments, particularly labor and resource markets [26, 28].

The main factor from this literature tested in this analysis is the effect of group size. Theory indicates that small to medium-sized groups may be better able to maintain the cooperation needed to manage an irrigation system than large groups [23]. The mechanism behind this relationship is that as the number of members in a group increases, transaction costs involved in monitoring and enforcing agreements among members increase, and to the extent that contractual relationships are formed in order to resolve conflicts, principal-agent problems may be exacerbated due to the increasing costs in obtaining information on the behavior of a large number of members.

2.2. Social-ecological systems, resilience, and robustness

There is a substantial literature that has related various attributes of social-ecological systems (SESs) to their resilience, robustness, or vulnerability to different types of disturbances. Much of this work has been led by members of the Resilience Alliance (http://www.resalliance.org). Anderies et al. [2] define a SES as a social system "in which some of the interdependent relationships among humans are mediated through interactions with biophysical and non-human biological units." User groups managing CPRs are one example of a SES.

This literature primarily uses the term resilience when analyzing the sustainability of SESs, and somewhat less frequently the concept of robustness. While sometimes used interchangeably, resilience and robustness have distinct scientific lineages, resilience coming primarily from ecology and robustness from engineering. A common definition of resilience is given by Holling [14], as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.” Resilience emphasizes the ability of a system to sustain self-reinforcing relationships between its components in the face of a disturbance. Anderies et al. [2] define robustness as “the maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of design parameters.” Carlson and Doyle [7] give a similar definition of robustness as “the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment.”

Robustness is used in this analysis of designed irrigation systems instead of resilience because it emphasizes the persistence of a particular feature or function of a designed system, rather than the magnitude of a disturbance an evolved system can face while maintaining a set of self-reinforcing processes or relationships, which can be quite difficult to measure empirically [8]. Because of this it is more amenable to empirical operationalization by measuring the persistence of an important feature the system was designed to maintain in the face of disturbances.

Robustness in a complex system is specific to a level within that system and to a particular disturbance. Social-ecological systems are complex systems constituted by many levels, where the units at each level interact to form units at a higher level. For example, certain farmers in New Mexico interact to form the next level of social organization known as acequias. In a multilevel system such an irrigation system, robustness at one level does not necessarily translate into robustness at other levels. A system may be robust at one level to a particular disturbance, while subsystems at lower levels may not be: a drought may cause several farmers to abandon their fields, while not causing an entire acequia to disintegrate. The level, or unit, of analysis in this study is the acequia. The concept of robustness is particularly appropriate for this study, given the availability of data of a critical system function over time at the geographic scale of an acequia: vegetation production, measured through remote sensing satellite imagery.

Robustness is also disturbance-specific: to meaningfully say a system is robust requires specifying that it is *robust to* a particular disturbance. Long-lasting, community-based irrigation systems like the acequias have successfully adapted to several types of disturbances in the past, particularly droughts. These past adaptations, however, do not ensure that the acequias will persist in the future, particularly in an increasingly connected socio-economic world that integrates local communities into a much larger political and economic system. A central tenant of theories dealing with robustness, resilience, and other concepts such as highly optimized tolerance (HOT), is that complex systems become vulnerable to one set of disturbances when they adapt to another set [8, 15]. "Complex systems must trade off the capacity to cope with some types of variability to become robust to others" [15].

2.3. Acequias in New Mexico and Taos valley

Figure 1 displays the study area. Taos valley is 2,070m above sea level and encompasses roughly 400km^2. The acequia-irrigated area in the valley is roughly 40km^2. There are 51 acequias in the valley. The main use of water in the valley is irrigation. The valley is bordered to the east and southeast by the Sangre de Cristo Mountain range, which supplies most of the available water through snowmelt, as precipitation in the valley itself is limited to roughly 13 inches per year.

2.3.1. Background

The acequias in New Mexico and in parts of southern Colorado are the descendants of the original Spanish colonists who migrated north along the Rio Grande from Mexico. Acequia farmers still use a form of flood irrigation that is not common in most of the United States, involving the clearing of unlined ditches in the earth to carry water to their agricultural fields. An acequia is at once the name for a community of users who employ a mix of private and common property rights implemented mostly by three elected commissioners and an executive mayordomo, as well as the main irrigation ditch that the community uses. While each member owns their private parcel of land and the ditch that immediately feeds it, the larger ditch and the water running through it are common property, meaning that to access water each member must adhere to an established set of community rules. Each acequia also has a biophysical geographic manifestation that is important for this research. This includes the area of land and the interconnected surface-groundwater system that supplies water to this land via irrigation canals and groundwater aquifers.

As of 1907, acequias are formally political subdivisions of the state of New Mexico. However, water and land rights regimes within acequias are independent of the state government. It is the mayordomo who is in charge of allocating water within each acequia, while the commission serves a variety of legislative and judicial roles. When disputes arise between them, no one acequia or acequia official has authority over other acequias. Instead, when droughts occur, mayordomos and/or commissioners from a set of acequias may meet in accordance with historical water sharing agreements. These agreements play an important role in the robustness of the acequias to droughts by supplying water through social means when it would otherwise be unavailable. Similar agreements have been found to increase robustness to disturbances in traditional irrigation systems [5].

2.3.2. Acequia hydrology

In order to fully understand how the acequias have historically persisted in a high desert environment, we need to understand both their social and biophysical features. A important set of work has been done related to the hydrological properties of the acequias [9, 11, 25]. This work has indicated the importance of the surface-groundwater relationship characterized by traditional acequia irrigation methods. There are two components to this. First, it has been found in other parts of New Mexico that acequias recharge shallow groundwater aquifers. "Seepage from ditches and flood irrigated fields performs the important function of recharging shallow groundwater…up to 60% of flood irrigation applications percolate below the rooting zone, and this field percolation in combination with ditch seepage leads to an increase in groundwater levels during the irrigation season." [11]. When upstream acequias irrigate simply by running water through earthen ditches, an important portion of the water they use percolates into the groundwater system. Secondly, groundwater that percolates upstream may seep up to the surface for downstream acequias to use. This attenuates the collective-action problem between upstream and downstream acequias. Interviewees commonly reported the availability of groundwater through springs, often during times of drought or when upstream acequias did not have any.

2.3.3. Modern situation

While the acequias have historically persisted in a high desert environment with recurrent droughts, their continued survival is very much in question, largely due to increasing population levels across the state of New Mexico. This has had two primary results: new users settling within the acequias' historically irrigated territories, and the expansion of urban centers that compete for water rights, and otherwise adversely affect the hydrology the acequias have depended on for irrigation. Examples of each are found on multiple rivers throughout New Mexico, with the most obvious cases being the areas surrounding Albuquerque and Santa Fe, where acequias that once existed now have entirely disappeared. Both processes are affecting the acequias in Taos valley as well.

New users in an acequia lead to the fragmentation of property rights, as those rights must be subdivided among a larger number of users. Over time, land rights within the acequias of Taos valley have been subdivided, largely as a result of inmigration of relatively wealthy individuals into the valley. "As per a historical analysis of the Assessor's Records, Taos County continues to experience a growth of approximately 230 to 250 new single family residences per year, 90 to 145 new condominium units per year, and approximately 105 to 130 new manufactured homes (mobile homes) per year" [29]. The majority of this growth is occurring in Taos valley, signifying a disturbance to the acequias there, as newcomers frequently do not abide by traditional acequia rules and customs aimed at relieving collective-action problems.

The primary source of urbanization in the valley is the town of Taos as outlined in figure 1. Urbanization represents a disturbance to the acequias both biophysically and socially. Socially, acequias that are within the border of Taos are more likely to deal with development pressures such as the transfer of their water rights to a newcomer. Biophysically, several acequias in the area have reported that urbanization and development, particularly the paving of new roads and parking lots, have physically disrupted the local hydrology they depend on in order to water their crops.

3. Methods

3.1. Data collection

Data was collected on seven variables, six independent and one dependent, in order to statistically test the six hypotheses above in a regression analysis. The unit of analysis in this study is an individual acequia, and all variables were calculated at this level. All 51 acequias in the valley were analyzed. Two databases were constructed to facilitate the analysis: a spatial database used for various calculations, and a non-spatial database that was ultimately used to store fields and values for the econometric analysis. A primary original source of data was a series of hydrographic surveys of the study area, conducted by the New Mexico Office of the State Engineer (OSE) from 1969 to 1971. These maps delineate each of the historically irrigated private parcels of land in the study area, along with the owner, the acequia it belongs to, the acreage, and the crop produced at the time. The maps also contain the rivers and main canals for each of the acequias in the area.

The first step in conducting the data collection was obtaining the hydrographic survey reports produced by the New Mexico Office of the State Engineer (OSE). Each of these maps was digitized into a spatial dataset. Since the acequias are the unit of analysis instead of individual members' parcels, these parcels were aggregated together in the spatial database to form larger geographic units corresponding to each acequia.

An additional source of data that was used was a series of testimonies given by senior acequia officers, testifying to the historic water-sharing practices they have maintained. Both these testimonies and the surveys were produced as a part of a water rights adjudication suit, commonly referred to as the Abeyta case, which was originally filed by the OSE as a part of its mandate to actively manage all of the water in the state. Finally, a set of on-site, informal interviews was conducted with 40 acequia officers (mayordomos or commissioners) from different acequias in order to obtain information on their historical agreements and other information relevant to their robustness or vulnerability to various disturbances.

3.2. Calculation of variables

Tables 1 and 2 describe the variables used in the econometric analysis. Table 2 describes various properties of each of the variables, including: which hypothesis the variable is included to test; whether or not a positive or negative relationship is expected between it and the dependent variable, NDVI; whether it is a social or biophysical variable, or both; whether it is a spatial or non-spatial variable; and whether it is a disturbance to an acequia or a property of an acequia. Table 3 provides the summary statistics for these variables, as well as for three other single-year measurements of the NDVI variable, whereas the measurement which is in tables 1 and 2 and used in the main analysis is a multi-year over time average. The following section describes the variables and the methods used to calculate them.

[TABLE 1 HERE]

[TABLE 2 HERE]

[TABLE 3 HERE]

NDVI

NDVI measures crop production over time for each of the acequias[1]. While irrigation systems as social-ecological systems have both biophysical and social functions, this study focuses on a biophysical function, crop production, for several reasons. First, through remote sensing imagery, data can be obtained for every one of the acequias in the study area over an extensive time period, from 1985 to 2008. Obtaining data on a social variable to the same extent would have been prohibitively difficult, if not impossible. Secondly, it is reasonable to assume that the production of crops is not only a primary biophysical output of irrigation systems, but also a reasonable proxy for a primary social function discussed in the CPR literature: collective-action. The reason for this is that in order to produce crops in a high desert environment, land requires external subsidies of water through irrigation, and due to the relatively low levels of technology available to the aceqiua members, collective action is still required in order to effectively supply this water to private parcels of land. Thus, crop production indicates important levels of collective-action. NDVI is defined by the following equation:

$$\frac{nir - red}{nir + red}$$

Where *nir* indicates the reflectance of an object or area in the near-infrared wavelengths while *red* indicates reflectance in the red wavelengths of the electromagnetic spectrum. Reflectance is the percentage of light of a particular wavelength incident upon an object that the object reflects. NDVI ranges from -1 to 1, depending on these two values. The higher the value is, the more vegetation is likely to be present, as healthy vegetation is highly reflective of near-infrared light and not very reflective of red light. While there are other environmental factors

[1] Initially, two approaches were used to calculate crop production values for each acequia: image classification and calculating an index of vegetation known as the Normalized Difference Vegetation Index (NDVI). Each process relies on the fact that distinct land cover types, such as bare soil or vegetation, exhibit characteristic reflectance patterns along different wavelengths in the electromagnetic spectrum, and can thus be identifed by observing these patterns in remotely sensed imagery. After calculating each measurement, the two were found to be highly correlated, strengthening the case for using either one as the measurement of the dependent variable. Ultimately, it was decided that NDVI would be the better of the two metrics.

that influence the vegetation index besides the presence of vegetation, NDVI has been consistently found to be "well correlated with crop biomass accumulation" (Lillesand et al. 2008, 540). It is worth noting that it is sensitive to precipitation levels, but these do not differ significantly among the Taos Valley acequias.

NDVI values are initially calculated for each pixel in a remotely sensed image, so some calculations must be done in order to translate these into values for the geographic area that an acequia composes. There are many ways to derive NDVI values for each of the acequias. Our goal was to arrive at one that maintained high conceptual validity with respect to the construct we wish to measure: robustness, where higher NDVI values *over time*, with a mix of disturbances occurring during this time period, are inferred to mean an acequia is more robust to one or more disturbances. Each of the disturbances and the acequias' responses to them occur over time. Thus, a single measurement at a particular point in time would not accurately measure an acequia's ability to maintain agricultural production over time in the face of various disturbances. Instead, a measurement over time is preferred.

To obtain over time NDVI values for each acequia, several steps were taken. First, images from Landsat satellites 5 and 7 were obtained through the United States Geological Survey's (USGS) Global Visualization Viewer (Glovis). Each image contains 7 spectral bands, corresponding to 7 different wavelengths along electromagnetic radiation. Images from the growing season (May to August) of each year from 1985 to 2008 were obtained. These images were only recently made freely available to the public by the USGS. Each of these images had been previously geometrically and radiometrically corrected by the USGS through what they refer to as their Level 1 Production Generation System.

A set of NDVI images was calculated by applying the NDVI equation to the red and near-infrared band values from each of the cells for every Landsat image. Following the creation of the NDVI images, a zonal analysis was conducted on each in order to derive statistics for each of the 51 acequias based on the distribution of NDVI values of the cells within their boundaries. This produced a mean NDVI value from the cells within each acequia from each image.

The steps discussed produced 25 averaged NDVI values for each of the acequias, one from each original Landsat image. Each of the 25 NDVI values for each acequia is a spatial average of the NDVI values of all the cells in that acequia's boundary. The final step was to calculate the average of these 25 values for each of the acequias. This produces an over time average NDVI value for each of the acequias as the dependent variable.

Acequia size

Historic size of the acequias was taken as the number of members established by the original OSE hydrographic surveys from 1969 to 1971. The actual number of members of each acequia are not given by these reports. Instead, a list of the owners of land parcels is given. An assumption was made in calculating the number of members that duplicate names across several parcels within an acequia represented the same individual, who then owned several parcels. Based on interviews, this appears to be a common feature within the acequias.

Land fragmentation and urbanization

The index of land fragmentation was calculated by comparing the number of individual parcels within each aceqiua as established by the hydrographic survey reports with the number of parcels in the same area as calculated by a spatial database produced by the Taos County Assessor's office in 2006. As the parcels from the hydrographic surveys were originally used to construct the polygons for the acequias, these lie perfectly within the them, whereas the parcels from the Assessor's data office do not. Therefore, in order to calculate the number of new parcels within each acequia boundary, centroids were first calculated for each new parcel, and the number of centroids then lying within each acequia were calculated to obtain the new number of parcels. The variable itself is simply the new number of parcels divided by the old number of parcels within an acequia's boundary. A higher value indicates a greater degree of land right fragmentation. The percentage of an acequia's area that lies within with the municipal area of Taos, as outlined in Figure 1, was calculated as a measurement of urbanization pressure on each of the acequias.

Groundwater availability and water agreements

To measure the extent to which groundwater is available to the each of the acequias, a geographic buffer was created around each of the main rivers in the area in order to simulate an "irrigated corridor" that Fernald et al. [11] describe. It is within this corridor between the river and a main canal that they report the greatest groundwater recharge occurring following an acequia's irrigation. The percentage of each acequias' irrigated land area that lies within this corridor was calculated to obtain a measurement for this variable.

The water agreement variable is binary, being a 1 for an aceqiua if is does have any agreements, and a 0 if it does not. In order for this variable to be coded as a 1, the acequias involved needed to exhibit a relatively formalized understanding amongst each one of them: more ad hoc, or member-level arrangements were not counted. The source of data for this variable was the Abeyta case testimonies and on-site interviews with farmers.

Hydric soils

Different soil conditions are potentially important in determining the amount of crops different acequias are able to produce. The source of information for this variable is the Soil

Survey Geographic (SSURGO) Database, run by the Natural Resource Conservation Service within the United States Department of Agriculture. This is a spatial database based on geographic "map units" represented as polygon features in an Arcgis shapefile, which are connected to tabular information in a Arcgis geodatabase.

In order to determine which soil property or properties to include in the analysis, zonal analyses were conducted in order to determine whether certain soil properties were positively correlated with NDVI values. Several properties from the SSURGO database were found to affect the NDVI values within different areas of the valley. These include soil texture, soil drainage class, cation exchange capacity, hydric conditions, distance to underlying water table, and irrigation land capability class[2]. The most important of these seems to be the presence of hydric soils, where hydric soils have higher NDVI values than non-hydric soils. Hydric soils have the following definition [21]:

"The concept of hydric soils includes soils developed under sufficiently wet conditions to support the growth and regeneration of hydrophytic vegetation. Soils that are sufficiently wet because of artificial measures are included in the concept of hydric soils. Also, soils in which the hydrology has been artificially modified are hydric if the soil, in an unaltered state, was hydric. Some series, designated as hydric, have phases that are not hydric depending on water table, flooding, and ponding characteristics."

Given Leibig's law of the minimum it is not surprising that, in an area with severe water scarcity, that hydric soils would be so positively correlated with increased vegetation in irrigated areas. Figure 2 shows the result of the zonal analysis for hydric soils. There are three categories: all hydric, partially hydric, and not hydric.

[FIGURE 2 HERE]

[2] "Land capability classification shows, in a general way, the suitability of soils for most kinds of field crops. Crops that require special management are excluded. The soils are grouped according to their limitations for field crops, the risk of damage if they are used for crops, and the way they respond to management" (Text from ArcMap Soil Data Viewer application produced by the Natural Resource Conservation Service). The classes range from 1 to 8, with higher numbered classes representing increasing limitations on land use for irrigation.

Additionally, it appears that the presence of hydric soils is an important factor in what makes other soil properties correlate with NDVI values. Table 3 gives a representative example of the patterns found. For this table, “hydric” is a weighted average of the hydric soil conditions in the zone defined by a particular soil property, where “not hydric” is coded as a 0 , “partially hydric” is coded as a 1, and all hydric is coded as a 2. For soil texture and the other soil properties analyzed (including irrigation capability class, drainage class, cation-exchange capacity, and distance to water table) higher NDVI values are positively correlated with increasing hydric values within the different soil categories.

The higher hydric and NDVI values within each soil category seem to associate with increased water retention and/or availability. Regarding soil texture, which is the proportion of particle sizes within a volume of soil, larger particles within soils are accompanied by increased porosity, which increase the ability of water to percolate below rooting depth. Thus, water will be better retained by soils with finer particles. The four categories of soil textures found within the acequias in Table 4 are listed in order of increasing NDVI values and hydric values, but also in terms of decreasing average particle size. Loam is a mixture of sand, silt and clay, with sand particles being the largest and clay particles being the smallest. Clay loam has larger amounts of small clay particles and less of the other two and thus smaller particles on average, while silty clay loam has just as much clay as a clay loam, but less sand more silt than a clay loam.

[INSERT TABLE 4 HERE]

As a result of this analysis, the hydric property of soils was considered to be a reasonable summary of various soil properties insofar as they affect vegetative growth in those areas. The final step in calculating this variable was to translate hydric properties of SSURGO map units, coded as 0, 1, and 2, into acequia-level attributes. To do this, an average “hydric” value was calculated for each acequia, weighting the values of each of the three hydric classes by the percentage of the acequia's land area they occupy.

3.3. Relationships between independent variables

Table 5 provides the Pearson univariate correlations between the independent variables[3].

[TABLE 5 HERE]

The relationship between groundwater availability and water agreements in particular is worth discussing. This is between groundwater availability and water agreements. Each variable accomplishes a similar function: providing a source of water to an acequia that it needs when regular surface water resources are scarce. Noting that acequias that have less access to groundwater are more likely to experience overall water scarcity, and that water agreements are historically formed in a response to water scarcity, we would expect there to be a negative relationship between these two variables. Indeed, this is what we find in Table 5 (-0.39). Additionally, the average value of groundwater availability for acequias involved in a water sharing agreement is 30.4% (meaning that 30.4% of their area overlies the irrigation corridor, where groundwater is more likely to be available), while the average value for acequias not involved in a water sharing agreement is 62.4%. The difference is significantly far from 0, with a p value of 0.0024. This indicates that the acequias involved in agreements to obtain water during shortages have significantly less access to groundwater than those that do not, which is a plausible reason for why they have those agreements.

[3] The low correlations, Table 5 also provides preliminary evidence that multicollinearity between the independent variables is not a concern, and this is further supported with variance inflation factors and condition index diagnostics from Belsey et al. [6].

4. Econometric models and results

The first column of Table 5 provides the pairwise correlations with NDVI and the other independent variables. Each of these correlations confirms the related hypothesis, except for the very slight negative correlation (0.05) between *water agreement* and *NDVI*, which implies little to no relation at all. Following this initial analysis, we turned to the regression models. Here, the vegetation index represented by NDVI for acequia *i* is assumed to be a linear function of the previously discussed independent variables:

(1) $NDVI_i = \beta_0 + \beta_1 AcequiaSize_i + \beta_2 LandFragmentation_i + \beta_3 Urbanization_i + \beta_4 GroundWater_i + \beta_5 WaterAgreement_i + \beta_6 Hydricsoils_i + \varepsilon_i$

Table 6 provides the OLS estimates of the Equation (1) model. The OLS model fits the data well, explaining 47 percent of the variation in NDVI. Also provided in the first two columns of Table 6 is the Jarque and Bera [16] test for normality of the dependent variable, the Koenker and Bassett [18] test for homoskedasticity, and a set of spatial regression diagnostics. Both the Jarque-Bera test and Koenker-Bassett test fail to reject their respective null-hypotheses, so attention is turned to the motivations of the spatial diagnostics.

[TABLE 6 HERE]

[FIGURE 3 HERE]

Intuitively, CPR-related social dilemmas are spatially oriented problems. That the individually rational behavior amongst each acequia might be problematic for all neighboring Acequia could econometrically manifest itself as spatial autocorrelation. Figure 3 overlays a bubble plot of the NDVI on a surface map of the acequias in the Taos valley, and visually there appears to be clustering of similar values among neighbors. In this situation, ordinary least squares could be biased, inconsistent, or both (Anselin, 1988). This can be modeled as either the spatial autoregressive model (SAR):

(2) $y = \rho W y + X\beta + e,$

or as the spatial error model (SEM):

(3) $y = X\beta + v$

$$v = \lambda W v + e.$$

In both models, the error term e is the traditional normal Gaussian error with constant variance, W is a normalized n x n weight matrix that identifies the spatial relationships, and X is the n x k data matrix of explanatory variables. The spatial relationships in W are determined by the first-order contiguity of land and water boundaries, and these relationships are indicated with non-zeroes in the off-diagonal elements and are row-stochastic.[4] While determining between Equations (2) and (3) is in practice an empirical question, intuitively, the spatial error model seems more appealing in our dataset. In SEM, there is unobserved heterogeneity that exhibits a spatial pattern, rather than there being actual dependence across observations in the vegetation index as you would have in SAR. That is, there is no actual causal mechanism between the growth of vegetation on one plot of land and production on nearby plots of land. Instead, the mechanisms is likely less direct: due to the mobility and cohesiveness of water, when it is available on one plot of land, its availability is likely increased on nearby plots of land as well, either on the surface or the ground. This in turn will favor the production of crops on nearby plots of land and produce spatial correlation in the NDVI values of the acequias.

[4] In place of the first order spatial weight matrix, we also estimated models with “nearest neighbor” weight matrices based on centroids. Qualitatively the results were very similar, but there was a lower model fit in those SEM regression and less intuitive appeal for modeling a irrigation system.

To distinguish between the SEM and SAR models, we employ the Lagrange Multiplier (LM) tests on the residuals of an OLS regression, as described in Kim et al. [17]. The LM-Error diagnostic is rejected at the 90 percent confidence level for NDVI, and is not rejected in the LM-Lag, suggesting that the appropriate model is the spatial error model[5]. If there is no misspecification, the only difference between SEM and OLS should lie in the standard errors. To test if observed differences between SEM and OLS coefficient estimates are statistically significant, which would suggest misspecification, the spatial Hausman test is also employed [24]. The results of the spatial Hausman test, reported in the last row of Table 6, indicate that the observed differences in the correlation coefficients are not statistically significant.

The final column of Table 6 presents the spatial error model estimates for NDVI, which reveals that the spatial autocorrelation had considerable effects on the standard errors, as several variables change in statistical significance. Land fragmentation and extent of urbanization lose their significance, while the availability of groundwater, having a water agreement, and the size of the Acequia gain statistical significance. The interpretation of SEM coefficient estimates is undertaken in the same manner as OLS, so that a coefficient represents the change in the dependent variable from a one unit change in the corresponding independent variable.

To check the robustness of the results, rather than using a time-averaged dependent variable for the units, we repeated this procedure for three selected years. First, 2008 is estimated as it is the most recent year of the data, to detect if the result is driven by historical matters that may or may not still be relevant. Secondly, we test the model over the index from 2000, which is interesting because it is one of several years in the data when a particularly severe drought occurred. Finally, we estimate it in 1985, the oldest data point in the series. The results of these regressions are reported in Table 7. An interesting result is that the variables do not

[5] The robust versions of the LM test [4] provided the same result, so they are not listed.

seem to change in significance or importance over time. This is particularly surprising for the land rights fragmentation and urbanization variables, given that these are both disturbances that have been increasing in the study area over the time period of 1985 to 2009, which would make us expect increasing statistical importance over time as well.

[TABLE 7 HERE]

The only difference in the diagnostics on Table 7 from Table 6 is that in the drought year regression, 2000, the spatial Hausman test rejects the null hypothesis that the OLS and SEM coefficient estimates are equal at the 90 percent confidence level, which suggests model misspecification. Nevertheless, the model estimates are qualitatively similar to the rest.

To gain more insight into the analytical significance of the coefficients in Tables 5 and 6, we turn to a set of calculations presented in Table 8. In Table 8, we have calculated the marginal effect of a one standard deviation increase in the independent variable both in absolute terms, and as a percentage of a standard deviation of the dependent variable[6].

[TABLE 8 HERE]

For example, the coefficient estimate on Acequia size in Table 6 is -0.032, the standard deviation of Acequia size is 0.515, so the marginal effect is -0.016 (-0.032×0.515). This change represents 20.1 percent of the dependent variable's standard deviation (-0.016/0.081).[7] Table 8 reveals that having a water agreement is clearly important in terms of qualitative significance, as it increases the vegetation index by more than half its standard deviation in all estimates. All the variables, statistically significant or not, have non-trivial analytical significance. For instance, while the proportion of the acequia's land that was urbanized was not statistically significant in

[6]Except in the case of the effect of having a water agreement, for which we only use the effect of going from zero to one, as it is an indicator variable

[7] The reported calculations were done in a spreadsheet with a higher degree of precision, so there is some differences reported due to rounding if a reader were to use the observed values in this paper.

any specification, a one standard deviation increase in this proportion reduced the vegetation index by about 20 percent of a standard deviation.

Based on the statistical evidence, each of the hypotheses seem reasonably well supported. As already mentioned, smaller acequias performed better over time than larger acequias (H1). The acequias are vulnerable to the fragmentation of land rights (H2) and urbanization (H3), as a standard deviation in each, respectively, reduces the vegetation index by about 20 percent of a standard deviation. Certain properties do make the acequias more robust to droughts by increasing access to alternative sources of water during them, either through groundwater sources (H4), or water sharing agreements (H5). Our results in Table 8 indicate that having a water agreement has a marginal effect equivalent to that of a two to three standard deviation increase in groundwater availability. Finally, soil properties associated with water availability and retention increase vegetative production (H6). In absolute value, the magnitude for these hydric soils had the largest marginal effect among the continuous variables.

5. Conclusions

This paper contributes to the research programs on CPR management and on robustness and resilience in SESs. It helps to illustrate that in order to understand social systems, one often has to understand the environmental factors they interact with, and vise versa. It also demonstrates the mix of technologies and scientific methodologies available, and in this case required, in order to conduct such an analysis. This mix of methods was enabled by the production of a unique dataset and the availability of both social and biophysical data on a common study area. As a result of this interdisciplinary approach, we were able to test several important hypotheses that relate to the sustainability of a social-ecological system.

These hypotheses were largely confirmed, and reflect the importance of understanding both the social and environmental aspects of the system. Both water sharing agreements and access to groundwater provide alternative sources to water that help the acequias maintain irrigation practices and produce crops in spite of periodic droughts. Additionally, particular soil properties associated with water retention help the acequias to produce crops in a dry environment. Smaller acequias are better able to maintain crop production per unit area than larger acequias, with a plausible mechanism for this being their lower transaction costs involved in monitoring and enforcements their internal agreements.

While the acequias have been responding to droughts for centuries and seem well-adapted to them, the novel disturbances of land right fragmentation and urbanization appear to be much more difficult for them to resolve. The acequias that have been more exposed to them are producing fewer crops than other acequias in the valley. In many areas around the world, increasing economic connectivity that these disturbances represent are impinging on the historical practices of community-based management regimes. Such connectivity may afford new opportunities, but we should not be surprised that it may come at a cost. In this case the cost, as revealed by in-person interviews with farmers in the valley, has involved decreased interdependence and solidarity both within and between acequias, as they are involved less in historic traditions and rituals, and more involved in the larger and more developed economy through wage-earning jobs and food markets.

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Figure 1: Taos Valley

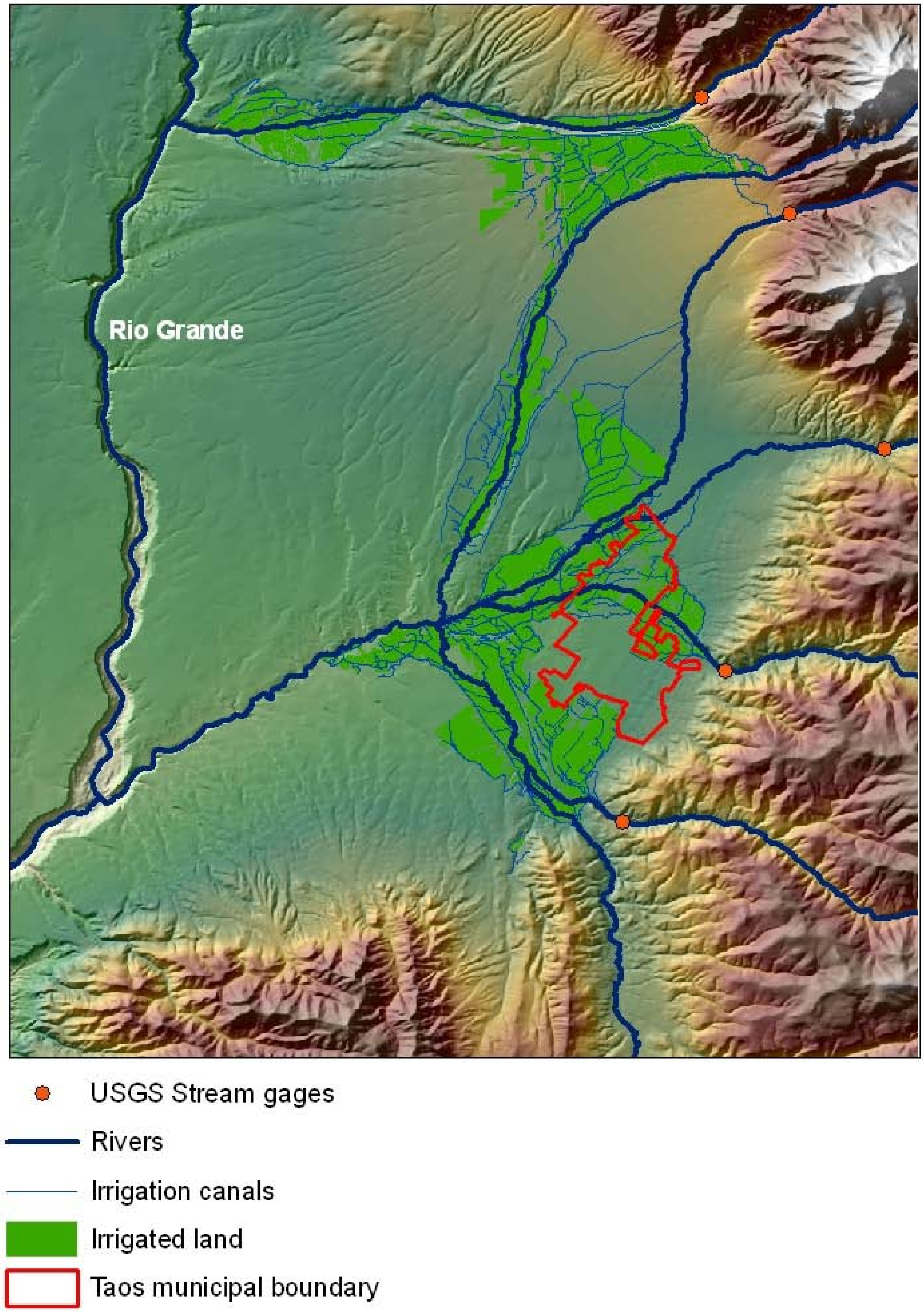

Table 1: Variable descriptions

Name	Description
NDVI	A spatial average of vegetation growth for an acequia's irrigated area using the Normalized Difference Vegetation Index (NDVI)
Acequia size	The number of members an acequia has historically had, as measured by OSE hydrographic surveys
Land fragmentation	Number of parcels of land in 2006 recorded by Taos County Assessor / number of parcels established by hydorgraphic surveys around 1970
Urbanization	The percentage of an acequia that lies within the municipal boundary of Taos
Groundwater availability	The proportion of an acequia that overlies the "irrigation corridor", where groundwater is more likely to be available
Water agreement	Whether or not an acequia has a formal water-sharing agreement with other acequias
Hydric soils	Presence of hydric soils within each acequia, as identified by the Natural Resource Conservation Service

Table 2: Variable Descriptions

Name	Hypothesis	Expected relationship	Social/physical	Geography	Type
NDVI	N/A	N/A	Biophysical	Spatial	Dependent
Acequia size	1	Negative	Social	Non-spatial	Property
Land fragmentation	2	Negative	Social	Non-spatial	Disturbance
Urbanization	3	Negative	Both	Spatial	Disturbance
Groundwater availability	4	Positive	Biophysical	Spatial	Property
Water agreement	5	Positive	Social	Non-spatial	Property
Hydric soils	6	Positive	Biophysical	Spatial	Property

Table 3: Summary Statistics

Variable	Mean	STD	Min	Max
NDVI	0.359	0.081	0.202	0.520
NDVI (t=2008)	0.364	0.082	0.205	0.525
NDVI (t=2000)	0.008	0.074	-0.161	0.164
NDVI(t=1985)	0.432	0.073	0.217	0.575
Acequia size	0.397	0.515	0.020	0.244
Land fragmentation	1.185	0.896	0.118	5.382
Urbanization	0.157	0.324	0.000	1.000
Groundwater availability	0.474	0.417	0.000	1.000
Water agreement	0.471	0.504	0.000	1.000
Hydric soils	4.063	2.576	0.000	9.186

Figure 2: Relationship between hydric soils and NDVI

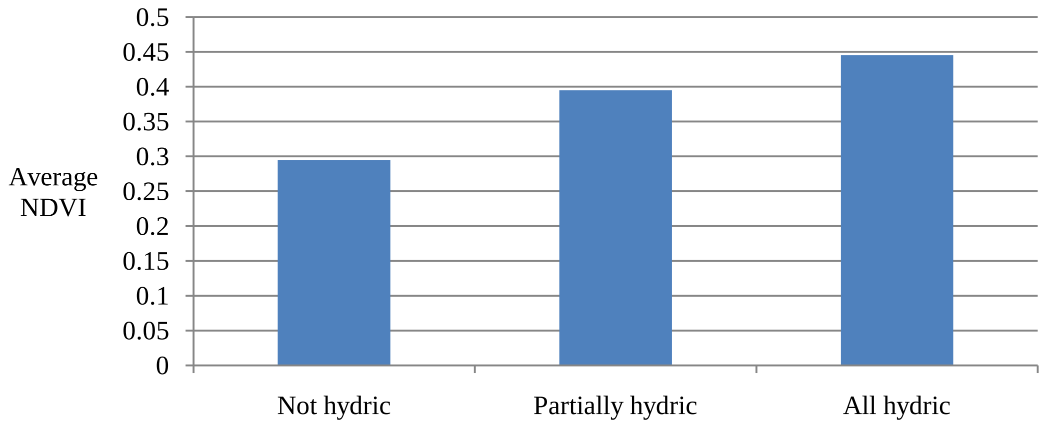

Table 4: Categories of Acequia Soil Texture

Texture	**Hydric**	**NDVI**
Very gravelly loam	0	0.25512
Loam	0	0.27782
Clay loam	0.62203	0.35526
Silty clay loam	1.28664	0.43399

Table 5: Pearson R Correlation Matrix

	NDVI	Acequia size	Land fragmentation	Urbanization	Groundwater availability	Water agreement
NDVI	1.00					
Acequia size	-0.33	1.00				
Land fragmentation	-0.38	-0.02	1.00			
Urbanization	-0.15	-0.01	0.06	1.00		
Groundwater availability	0.51	-0.37	-0.28	-0.14	1.00	
Water agreement	-0.05	0.52	-0.25	-0.05	-0.39	1.00
Hydric soils	0.48	-0.54	-0.03	0.25	0.51	-0.39

Figure 3: Spatial View of Vegetation Index (NDVI)

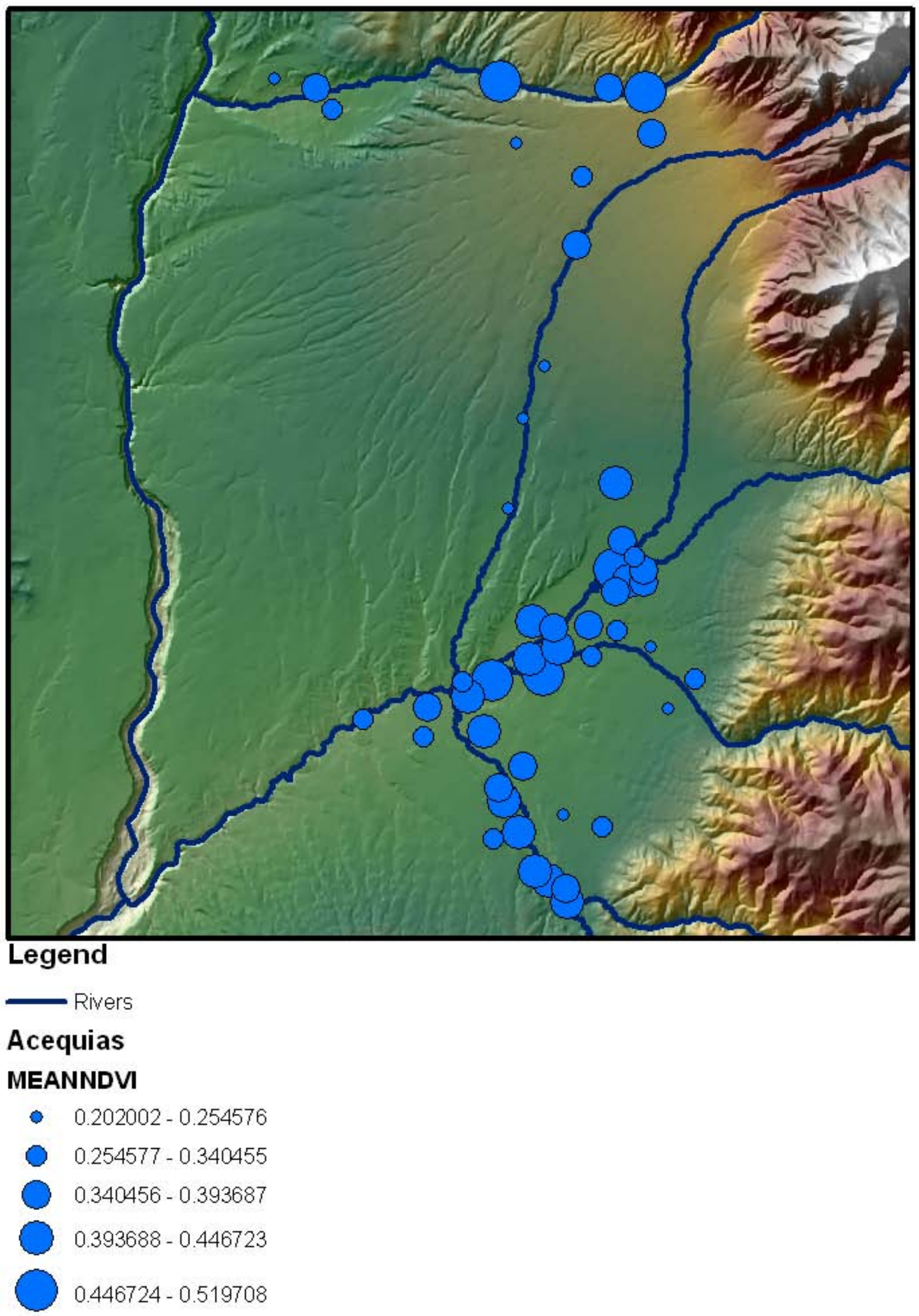

Table 6: Regression Results

	Ordinary Least Squares	Spatial Error Model
Constant	0.316 ***	0.303 ***
	(0.034)	(0.032)
Acequia size	-0.021	-0.032 *
	(0.023)	(0.019)
Land fragmentation	-0.023 **	-0.016
	(0.011)	(0.010)
Urbanization	-0.051 *	-0.052
	(0.030)	(0.032)
Groundwater Availability	0.042	0.058 **
	(0.029)	(0.026)
Water agreement	0.030	0.045 **
	(0.023)	(0.021)
Hydric Soils	0.013 ***	0.011 ***
	(0.005)	(0.004)
λ		0.372 **
		(0.186)
Sample Size	51	51
R^2	0.474	0.529
JB	1.630	
KB	1.340	
LM-Lag	1.140	
LM-Error	3.269 *	
S-H Test	8.705	

Notes: Abreviations: Jarque-Bera test for normality of dependent variable (JB), Koenker-Bassett test for heteroskedasticity (KB), Langrange Multiplier (LM), Spatial Hausman Test (S-H).
Statistical significance indicated at the .01, .05, and .10 level by ***, **, and *, respecitvely.

Table 7: Sensitivity analysis

	2008		2000		1985	
	OLS	**SEM**	**OLS**	**SEM**	**OLS**	**SEM**
Constant	0.317 ***	0.303 ***	-0.040	-0.048	0.414 ***	0.401 ***
	(0.034)	(0.031)	(0.034)	(0.031)	(0.034)	(0.031)
Acequia size	-0.021	-0.035 *	-0.020	-0.040 **	-0.017	-0.032 *
	(0.023)	(0.019)	(0.023)	(0.019)	(0.022)	(0.019)
Land fragmentation	-0.023 **	-0.016 *	-0.021 *	-0.012	-0.026 **	-0.021 **
	(0.011)	(0.010)	(0.011)	(0.010)	(0.011)	(0.010)
Urbanization	-(0.052) *	-(0.048)	-(0.037)	-(0.045)	-(0.042)	-(0.042)
	0.030	0.032	0.030	0.032	0.030	0.032
Groundwater Availability	0.041	0.057 **	0.025	0.036	0.034	0.053 **
	(0.029)	(0.026)	(0.029)	(0.025)	(0.029)	(0.026)
Water agreement	0.029	0.049 **	0.029	0.046 **	0.031	0.051 **
	(0.023)	(0.021)	(0.023)	(0.021)	(0.023)	(0.021)
Hydric Soils	0.014 ***	0.012 ***	0.011 **	0.010 **	0.008	0.006
	(0.005)	(0.004)	(0.005)	(0.004)	(0.005)	(0.004)
λ		0.376 **		0.409 **		0.350 *
		(0.186)		(0.180)		(0.190)
Sample Size	51	51	51	51	51	51
R^2	0.492	0.550	0.373	0.461	0.372	0.436
JB	1.707		0.518		4.876	
KB	1.473		1.770		7.521	
LM-Lag	1.275		2.130		0.318	
LM-Error	3.563 *		4.060 **		2.820 *	
S-H Test	6.819		11.571 *		8.209	

Notes: Abreviations: Jarque-Bera test for normality of dependent variable (JB), Koenker-Bassett test for heteroskedasticity (KB), Langrange Multiplier (LM), Spatial Hausman Test (S-H).

Statistical significance indicated at the .01, .05, and .10 level by ***, **, and *, respecitvely.

Table 8: Analytical significance of marginal effects

		All Years		2008		2000		1985	
Variable (x_k)	Δx_k	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$	$\beta_k \Delta x_k$	$(\beta_k \Delta x_k)/\sigma_y$
Acequia size	0.515	-0.016	-20.1%	-0.018	-21.8%	-0.021	-27.8%	-0.017	-22.6%
Land fragmentation	0.896	-0.014	-17.8%	-0.015	-17.8%	-0.011	-14.4%	-0.019	-25.6%
Urbanization	0.324	-0.017	-20.7%	-0.015	-18.8%	-0.015	-19.7%	-0.014	-18.7%
Groundwater Availability	0.417	0.024	29.9%	0.024	29.1%	0.015	20.1%	0.022	30.1%
Water agreement	1.000	0.045	55.9%	0.049	59.2%	0.046	61.5%	0.051	69.2%
Hydric Soils	2.576	0.029	36.2%	0.032	38.5%	0.025	33.4%	0.016	21.9%

Notes: Δx_k is the change in the independent variable, which is one standard deviation for the continuous variables and a unit change for the water sharing agreement dummy. The corresponding correlation coefficient β_k is from the SEM results in Tables 6 and 7. The standard deviation of the dependent variable is σ_y.