Model evaluation and sensitivity analyses of an acequia community irrigation system dynamics model

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Abstract: Agriculture-based irrigation communities of northern New Mexico, forms of Coupled Natural-Human and Common Pool Resources systems, have survived for centuries despite the arid environment in which they reside. These irrigation communities provide a broad array of ecosystem goods and services, which are being threatened by regional population growth, urbanization, gentrification, economic development, climate change, and other factors. After providing some background and context on an acequia model currently in development, we briefly describe some early calibration metrics, including behavior reproduction and Theil inequality statistics. These measures indicated that the model is reproducing similar trends to those in the observed system. With this information, we then conduct several sensitivity tests to explore model performance to changing economic conditions (rate of rising input costs), social factors (community mutualism), and management decision factors (responsive to land use indicators). We find that the model outputs showed marked changes to various experimental conditions. As more data become available to test model assumptions more robust and in-depth insights may be possible.

Keywords: acequia, irrigation, New Mexico, model calibration, evaluation, sensitivity analysis

1. Introduction

Agriculture-based communities of northern New Mexico have survived for centuries despite the challenges of the arid environment in which they reside. This has been achieved through a system of community managed irrigation systems, called acequias [derived from Arabic as-sāqiya, meaning water conduit] brought to the region by Spanish colonists (Ackerly 1996). The term acequia refers to both the gravity-based systems of diverting river water to agricultural fields as well as to the social organizational structure of community-based water management (Mayagoitia et al. 2012). Such systems have been described as coupled natural human (CNH) systems (Fernald et al. 2012), where sustainability is rooted in the connectivity between the natural and human elements within a system, as well as common pool resource (CPR) systems (Cox and Ross 2011), where resources are managed by decentralized user-groups.

Today, however, the sustainability of acequia communities face many challenges - including climate change, demographic shifts and gentrification, increasing needs for economic relief, pressures for economic development, urbanization in the surrounding region, and threats from downstream users to deliver more water (Mayagoitia et al. 2012). Agricultural production can no longer support the desired standard of living, and increasing urbanization in northern New Mexico has provided economic opportunities outside the traditional community structure. Demand for rural land continues to grow as wealthy individuals from urban cities continue to buy land for telecommuting or retirement purposes, resulting in agricultural and community fragmentation. Less acequia water diversions for agriculture can hinder the delivery of ecosystem goods and services (e.g., groundwater recharge; riparian habitat) but, more importantly, endanger the basic operations of the system itself. Despite these forces, acequia members have maintained a sense of place and remain optimistic about sustaining the traditional acequia systems (Mayagoitia et al. 2012) and have organized new institutions to support acequia sustainability (e.g., the New Mexico Acequia Association founded in 1990).

The objective of this work is to describe sensitivity analyses conducted on a previously developed system dynamics (SD) model of acequia communities in northern New Mexico. We first outline the acequia community study areas, their structure, behavior over time, and the development of the model's Dynamic Hypothesis. Then a description of the SD model is given along with the various sensitivity tests run on the model. Lastly, we discuss the sensitivity analysis and future research aims of the acequia SD model.

2. Acequia locations, description and context

Communities that were established and continue to practice acequia-based management are located throughout New Mexico and southern Colorado (Figure 1), with the majority being in northern New Mexico. These communities lie along the upper and middle Rio Grande basin, including portions of the Rio Chama, Rio Santa Cruz, Taos valley, upper Pecos basin, Albuquerque, and El Paso regions (Ackerly 1996). These systems generally flow south toward Mexico and Texas with the majority of discharge originating from snow-pack in the mountainous watershed reaches. Acequia communities generally lie in small, narrow valleys ("ribbons of green") just below the mountains or along the tributary system that discharges to the Rio Grande corridor. To take advantage of existing instrumentation and networks of local expertise, study sites were selected to build on sociocultural and hydrologic research studies already completed (e.g., Ochoa et al. 2007; Ochoa et al. 2009; Mayagoitia et al. 2012). Strong community relationships have been developed at three detailed study sites: Rio Hondo, a tributary to the Rio Grande main stem; El Rito, a tributary to the Rio Chama; and Alcalde, which is on the main stem of the Rio Grande. These sites are excellent for testing regional connections between the Albuquerque urban area on the Rio Grande downstream and the rural study sites upstream.

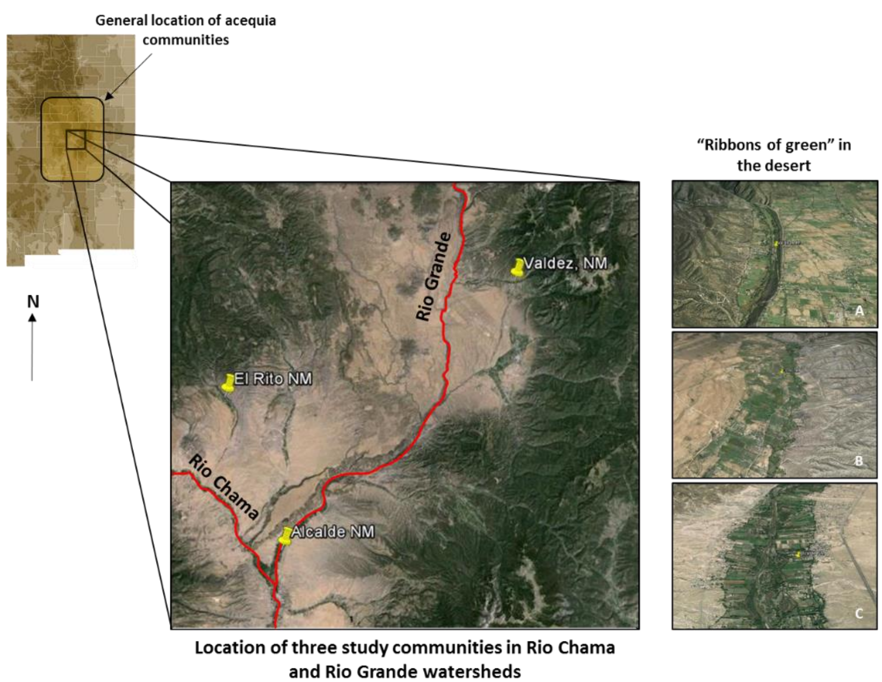

Figure 1. Location of acequia region within Colorado and New Mexico, USA, and the three study communities in northern New Mexico. Panel images A (Valdez), B (El Rito), and C (Alcalde) show the vegetative landscape, or "green ribbons", that persist in the arid region due to acequia water management.

3. Materials and methods

We used System Dynamics (SD) methodology to integrate the social, economic, ecologic, and hydrological connections that interact within an acequia community.

3.1. Model development and overview

Stakeholders were engaged with a research team of experts from various fields to describe acequia structures, connections, and challenges (Mayagoitia et al. 2012; Fernald et al. 2012). A Dynamic Hypothesis was then constructed to guide the model focus and purpose (Figure 2). The SD model incorporates economic, social, and hydrological perspectives, which operate over a fixed land base owned by acequia parciantes (i.e. community members). Endogenous components (i.e., internally driven stock-and-flow structures) include land, land use and time management decisions of parciantes, and community population dynamics (Figure 3). Exogenous components include labor wage rates, commodity prices and production costs, and climate inputs such as precipitation, snowfall, and annual temperature fluctuations, which drives stream flow and crop production systems and ultimately agricultural profitability. The model was formulated using object-oriented commercial software package, PowerSim Studio™ V. 10, using a monthly time-step over a 40 year simulation horizon (1970-2010). The same basic model structure was utilized for all three acequia communities; however, each acequia is represented by community specific initial conditions, rate functions, etc. The full list of model variables and equations are provided in Supplementary Material.

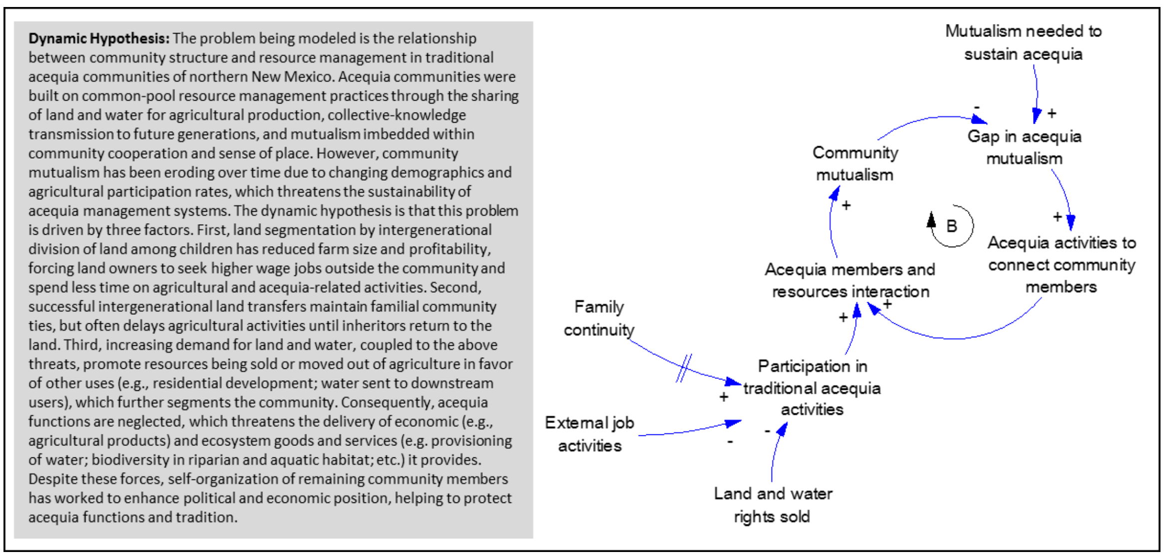

Figure 2. Dynamic Hypothesis and Causal loop diagram of the acequia problem being modeled.

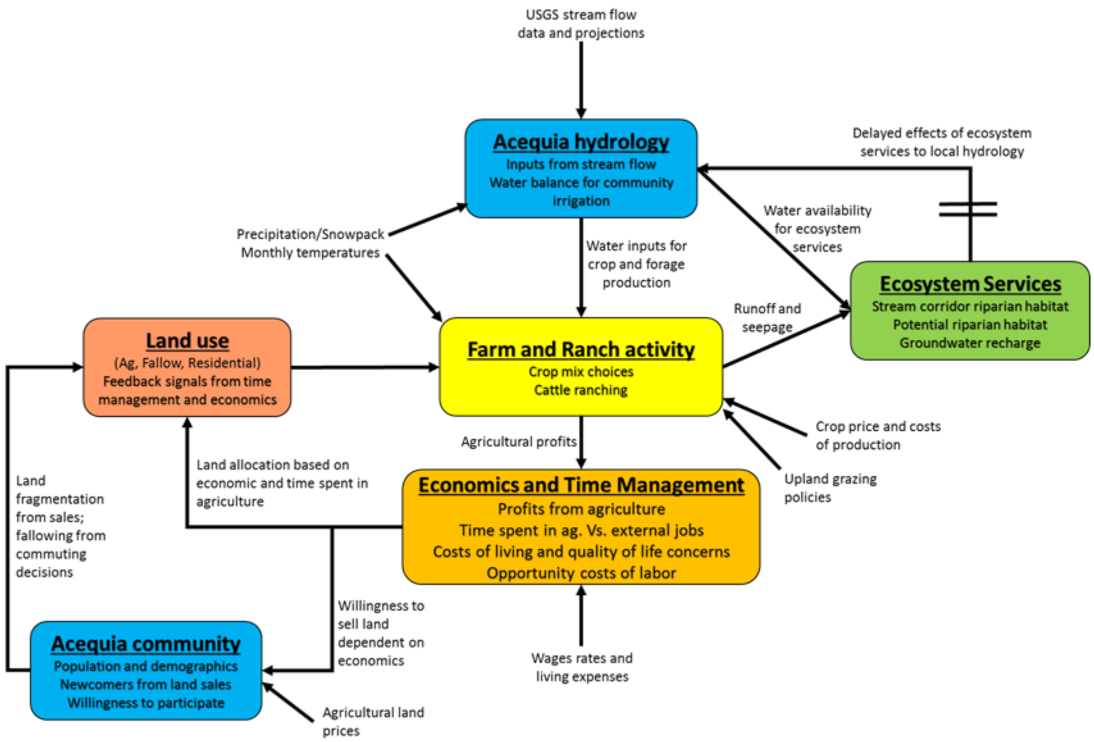

Figure 3. Conceptual diagram showing the major endogenous components and the linkages between them.

3.2. Reference modes, calibration, and evaluation procedures

The model's reference modes include stream flows, agricultural profits, community size and demographics, and land use (agricultural and fallow land, residential growth, and riparian habitat). Model outputs of each of these variables were compared to historical data. The reference mode time horizon was the time period 1969 through 2008 (social components) and 1969 through 1985 (hydrology components). The major methods we used for judging model adequacy included behavior reproduction tests and Theil inequality statistics (a method of decomposing Mean Square Error, MSE, of predicted values). We acknowledge that there are more comprehensive tests that should be included in model heuristics. Sterman (2000), Oliva (2003), and Tedeschi (2006) provide systematic approaches to SD model calibration and evaluation. More comprehensive tests are beyond the scope of this model sensitivity paper.

3.3. Sensitivity analyses

Sensitivity analysis is performed to test robustness and determine uncertainty in any assumptions used to create the model. Although not impossible, comprehensive sensitivity analyses are time intensive to organize and challenging to analyze. Another approach is to focus model sensitivity testing on relationships and parameters suspected to be both highly uncertain and likely influential. To achieve this we generated a list of all model variables and compared them to components in the real world system. We eliminated from testing those variables for which existing data is accessible or where confidence in the parameter values was relatively strong. By elimination, we arrived at an abbreviated variable list (Table 1) and selected three variables for testing. Sensitivity analyses can be conducted via numerical, behavioral, or policy sensitivity tests. Numerical sensitivity occurs when a changed assumption changes the numerical value of the results. All models possess such numerical sensitivity. Behavioral sensitivity occurs when a changed assumption changes the patterns of model behavior, while policy sensitivity occurs when a changed assumption reverses the impacts of a proposed or existing policy. An overview of the model tests conducted is provided (Table 1).

Table 1. Overview of potential and selected variables for sensitivity analysis with calibrated and tested values.

	Model components and variables			**Sensitive?[1]**		
Time in agriculture determinants		**Calibrated value**	**Tested values**	Ag Profit	Community	Land in Production
*	Weight of acequia mutualism	1	0, 0.5	*Yes*	*Yes*	*Yes*
	Weight of agriculture-preference					
	Weight of life-time earnings					
Economics						
*	Input cost growth rate	0.2% month^{-1}	0%; 0.47% month^{-1}	*Yes*	*Mixed*	*No*
	Land use classification preferences					
Hydrology						
	Seepage rates					
	ET parameters					
	Consumptive Irrigation Requirements					
Community						
	Generational transfer rates					
	Newcomer acclimation rates					
	Residential development required					
Land						
*	Parciante responsiveness to indicators	50%	20%; 100%	*Yes*	*No*	*Yes*
	Residential:agricultural price per acre					
	Lease price:land value ratio					
	Ag lease rate on newly purchased land					
	Upland size and productivity					
*Sensitivity tests included in this paper; remaining tests will be explored in the future as remaining components of the model are calibrated to existing data.				[1] Numerical sensitivity based on mean changes compared to model prediction error (mean bias).		

4. Results and Discussion

4.1. Behavior reproduction and Theil statistics

The first community calibrated was Alcalde, NM, using agricultural profits and stream flows as the reference modes. Model predicted agricultural (farm level) profit was compared to Rio Arriba county agricultural profit trends over the period 1969-2008. Pearson correlation coefficient (r), a measure of goodness for behavior reproduction, was 0.4367 (r^2=0.19). Although a low correlation value shows limited model ability to mimic point-by-point observed data, resulting Theil inequality values showed systemic similarity between observed and predicted values. Ending model bias estimates of 0.006 (mean), 0.024 (variance), and 0.969 (covariance) showed that model average values and variability were near historical levels. Some of the model bias (particularly during the first half of the simulation) is expected since agricultural prices used in the profit function are U.S. national averages (alfalfa, wheat, cattle) and orchard prices derived in a different geographic region (Washington state, U.S, for which data exist over the simulation horizon). These predicted values can certainly be improved with local price data for all commodities of interest, however data sources for such inputs appear to lacking or sporadic in nature. Model predicted stream outflows showed much stronger calibration values to observed values. The

Pearson correlation coefficient between predicted and observed flows was 0.996 (r^2=0.993). Most of the model bias in flows is expressed in the covariance (0.699) and variance (0.259) of predicted values, while mean bias was remarkably low (0.040). Although low errors in mean were encouraging, such a high value in the proportion of error residing in the variance column is somewhat alarming, and may warrant revising or extending the hydrology component of the model (e.g., groundwater-surface water interactions).

4.2. Sensitivity analyses

The majority of our early sensitivity tests resulted in marked change in model outputs (Table 1). The first variable tested was the mutualism decision weight (part of the Dynamic Hypothesis; one of three factors in determining an average parciantes' time allocation to agricultural activities, along with agriculture-time preference and lifetime earnings). All three output variables showed sensitivity to changing mutualism weight (Figure 4). Reducing weight of mutualism on time allocation to agriculture decisions gave greater weight to agriculture preference and lifetime earnings, which resulted in greater land in production and therefore greater agricultural profits, while slowing community population growth. These had positive effects on agricultural profit. Community population is highly influenced by land sales and newcomer introduction and acclimation. Land sales, however, are dependent on parciantes' willingness to sell, which are partly determined by agricultural profits. With improved profit levels, fewer parciantes were willing to sell and therefore fewer newcomers were added to the community.

The model sensitivity to the second test variable, input cost growth rate (0.2% $month^{-1}$), showed mixed results (Figure 5). As expected, increasing or decreasing costs (0.47% or 0% $month^{-1}$) resulted in decreasing (or increasing) profit levels. Although a substantial component, land use was relatively unchanged. This was most likely due to equal weights between community mutualism, agriculture time-preference, and lifetime earnings. Since land use in production was already in a decreasing trend, profit would have to be improved much more dramatically to see an increase in land use. Finally, model sensitivity to parciante responsiveness to land use indicator variables showed small but consistent deviations from model calibrated scenarios (Figure 6). More responsive parciantes resulted in greater profits, less land in agriculture, and increase community population compared to the less responsive parciante scenario.

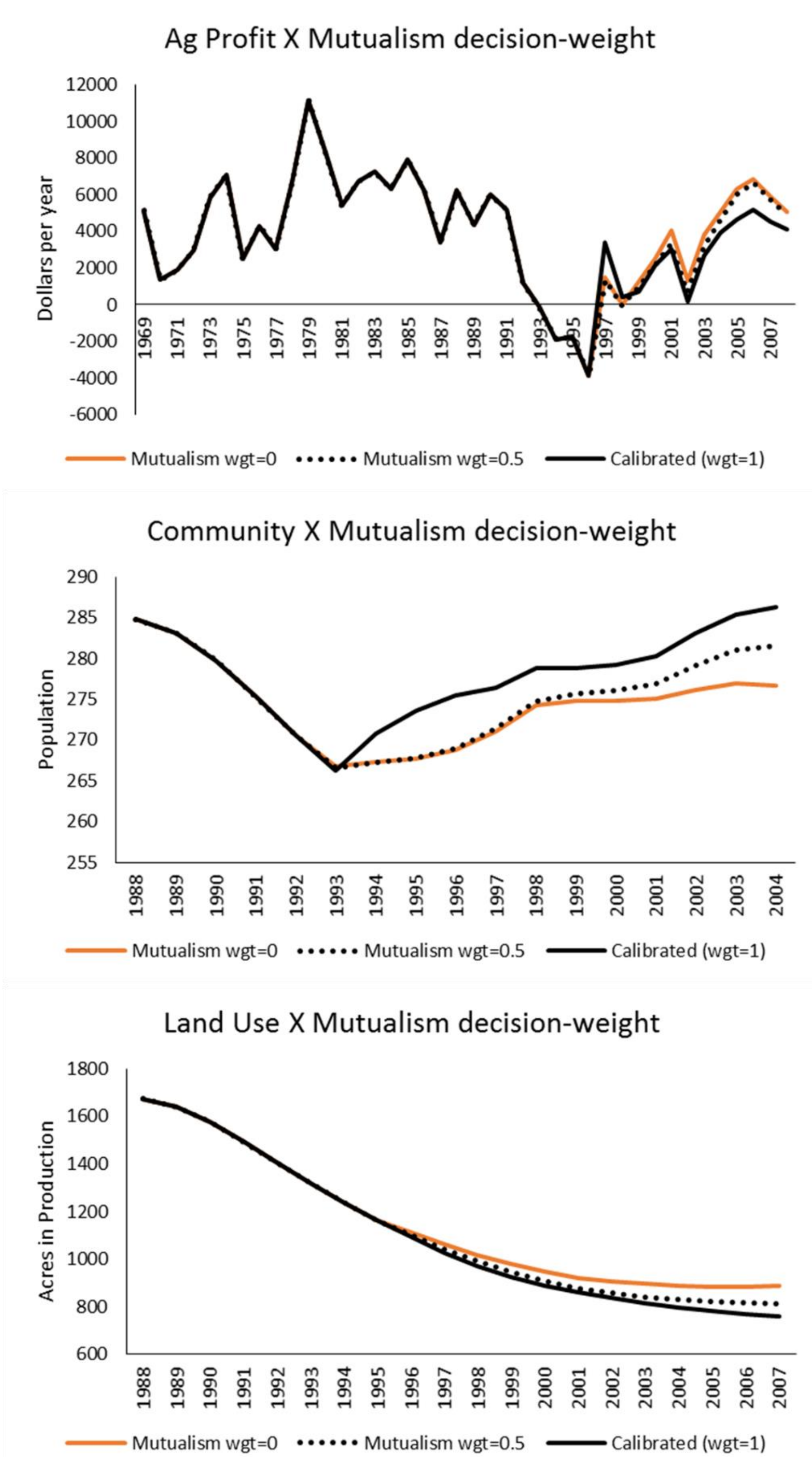

Figure 4. The impact of Mutualism decision-weight (in the Time in agriculture component) on: 1) Ag Profits; 2) Community (population); and 3) and Land Use (acres in production).

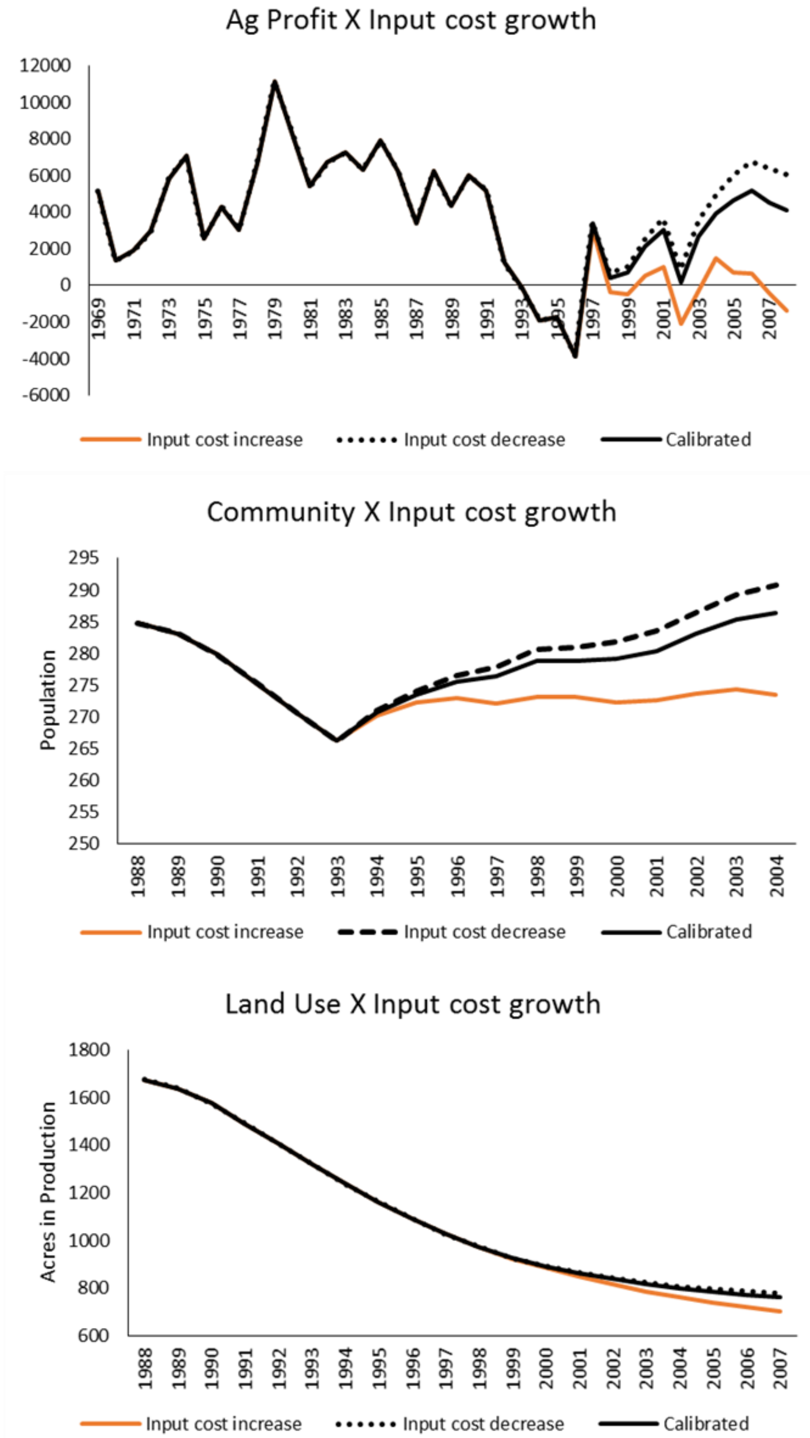

Figure 5. The impact of Input costs growth rates on: 1) Ag Profits; 2) Community (population); and 3) Land Use (acres in production).

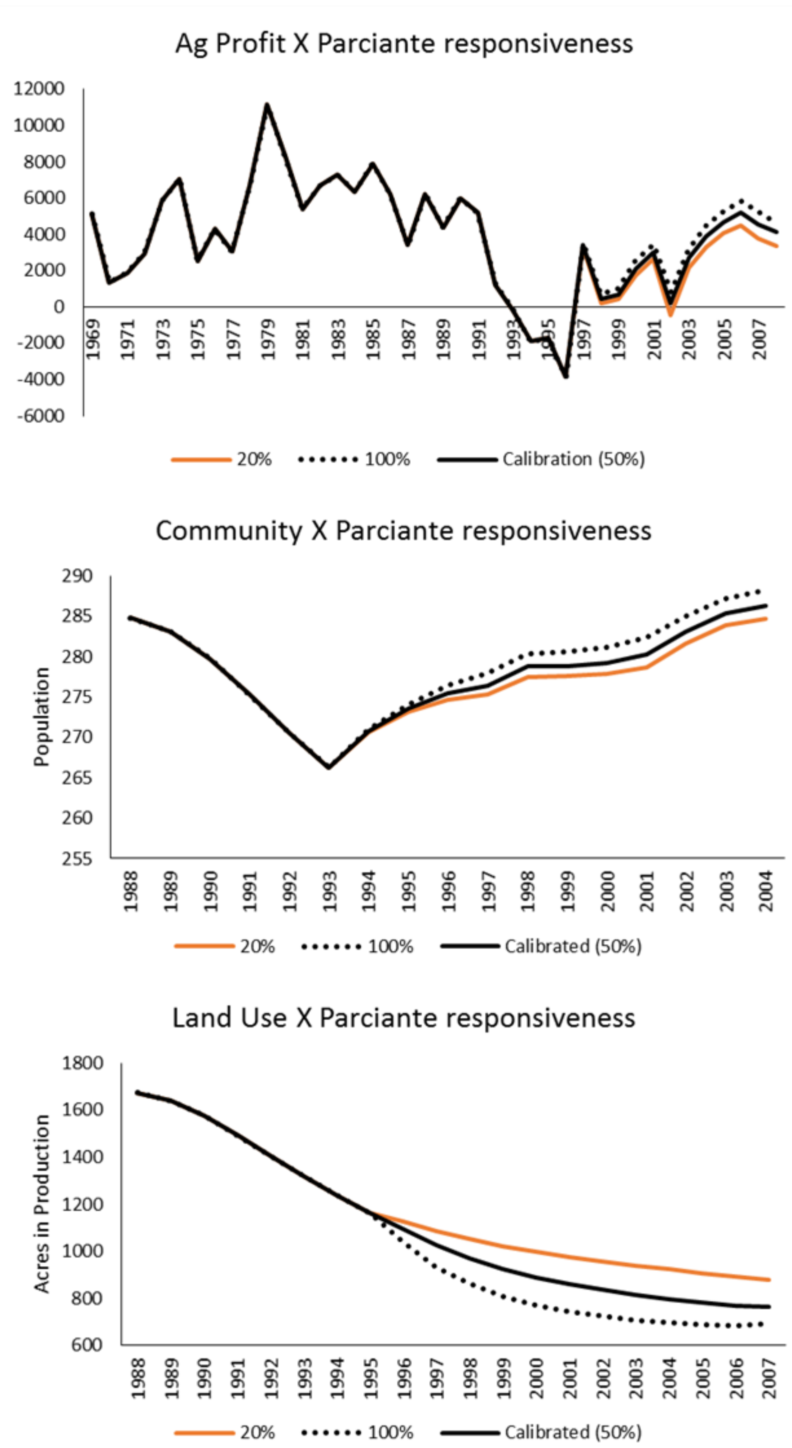

Figure 6. The impact of Parciante responsive to land use signals on: 1) Ag Profits; 2) Community (population); and 3) Land Use (acres in production).

5. Conclusion

The model presented here is an ongoing work to investigate the sustainability and resiliency of acequia communities in northern New Mexico. While knowledge of the complex interrelations of community, economics, ecology, and hydrology has advanced rapidly in the last 20 years, no model to-date has quantified these connections for scenario testing or robust analyses of potential system behavior in the face of continuous climate, economic, and social changes occurring in the region. We theorize that community sustainability and resilience are rooted in acequia-based connectivity, i.e., the communication and interaction between acequia members and the land and water resources they manage. We posit that traditional acequias create and sustain linkages between natural and human systems that increase community and ecosystem resilience to stressors, such as climate change and economic growth. After initial model development, calibration measures showed strong signs that the model is capable of reproducing observed patterns. Additional data sources are currently being mined or created (e.g., land uses and community demographics) in order to continue calibration of the model; these datasets will also aid in sensitivity testing.

This SD model will be the first model capable of testing for acequia sustainability and resiliency. Future work includes robust sensitivity and scenario testing to identify ‘tipping points’ from which the acequia structure cannot recover. We also aim to integrate this model with previous SD hydrology models in the region that will expand the boundary and number of feedbacks. This will broaden the potential audience and model users from acequia community stakeholders alone to include regional stakeholders and public policy makers.

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