Institutions of Self-Governing Irrigation Systems and Climate Change Adaptation in the Upper Rio Grande Basin

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INSTITUTIONS OF SELF-GOVERNING IRRIGATION SYSTEMS AND CLIMATE CHANGE ADAPTATION IN THE UPPER RIO GRANDE BASIN

by

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Self-governed irrigation systems cover about three quarters of global irrigated cropland, are essential to meeting global food security, and are threatened by climate change. Maintaining and improving irrigation performance depends on institutions, the rules, norms, and strategies used to organize economic behavior. However, the influence of institutions on irrigation performance is ambiguous and context dependent, as the shortcomings of decades of “panaceas” have shown. Therefore, for the benefit of academics, policy-makers, water managers, and irrigators alike, this dissertation asks the question: how do rules interact with context – specifically, biophysical context, other rules, and cultural norms – to influence irrigation performance in self-governing irrigation systems under climate change? To answer this question, the following chapters investigate three essential institutional features of irrigation systems and other long-lived common pool resource regimes: de facto access rights, allocation and distribution rules, and monitoring rules. The empirical chapters use original data to investigate the Upper Rio Grande Basin of North America, where Spanish and American self-governing irrigation systems have been adapting snowmelt-driven irrigation to a high desert valley for over 350 and 150 years, respectively, and have recently faced signals of climate change. Following the Institutional Analysis and Development framework and Common Pool Resource theory, this dissertation develops three arguments. First, de facto Prior Appropriation water rights are a reliably strong influence on irrigation performance, but they significantly interact with biophysical context such
that *de facto* water rights have little to no influence. Second, during water scarcity, rules for flexible water allocation and rotational water distribution interact with each other and with water availability to influence irrigation performance differently at different locations within an irrigation system, with implications for inequality and continued collective action. Third, historical selection pressures are associated with institutional and technological features of irrigation systems and internalized norms. These norms interact with monitoring rules to influence the amount and equality of crop production and can conflict with water allocation rules in ways that harm performance in scarcity. Collectively, these arguments highlight the importance of a contextual, diagnostic approach to policy change and the need for further investigation into self-governing irrigation systems under long-term and accelerating climate change.
To the commons that sustain us.
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CHAPTER 1

INTRODUCTION

1.1. The Tragedy of the Commons and Climate Change: Compounding Problems of Self-Governing Irrigation Systems

In the coming century three billion more people will need to be fed (UNESCO, 2012). Much of that food will derive from irrigation; irrigation of crops is responsible for 40 percent of the world’s food supply and is expected to provide most new food (UNESCO, 2012). Complicating matters, climate change threatens the water supply to many irrigation systems (FAO, 2012; Gleick, 2003, 2010). Responding to climate change and expanding food production is largely in the hands of irrigators themselves; worldwide, approximately three quarters of irrigated cropland and one third of all cropland relies on small-scale, self-governed irrigation systems (Mabry, 1996).

In the arid Western United States, irrigation is a necessity for agriculture (Powell, 1867) and produced $152B in sales in 2012 (USDA, 2017). In the state of Colorado, just over half the farmland is managed by self-governing irrigation systems (Sax et al., 2006; USDA, 2012a), and about 80 percent of surface flows begin as snowpack (CCC, n.d.). Because irrigators, especially those reliant on snowmelt, are vulnerable to the effects of climate change, irrigators in the American
Southwest face challenges to adapt (Barnett et al., 2005; Cox, 2014a; Cox & Ross, 2011; Fernald et al., 2012; Janssen & Anderies, 2013; Meza & Wilks, 2012; Quiggin et al., 2010; Smith, 2014; Vicuña et al., 2012; Villamayor-Tomas, 2012). Snowpack is expected to decline across the Southwest due to climate change, with decreasing stream flow in the Upper Rio Grande Basin (URGB) especially (Lukas et al., 2014; USBR, 2013). Indeed, there have already been observed changes in temperature, and therefore frost-free season and onset of peak stream flow, in the Colorado portion of the URGB (Lukas et al., 2014; Mix et al., 2009, 2011, 2012) commonly known as the San Luis Valley (SLV). While institutional analyses of developing nations’ irrigation systems are relatively common in the literature (Cardenas et al., 2013; Janssen et al. 2011, 2012; Meinzen-Dick, 2007, 2014; Meinzen-Dick et al., 2018), studies of developed nations tend to focus on the technical and engineering aspects of irrigation performance, such as irrigation efficiency, water use efficiency, and water productivity (van Halsema & Vincent, 2012). This dissertation seeks to address this limitation by providing a detailed institutional analysis of self-governing irrigation systems in a developed country.

Independent of climate change, irrigators already confront serious challenges managing their irrigation systems due to the innate qualities of these systems and periodic drought. Like all common pool resources (CPRs), irrigation systems potentially face a “tragedy of the commons” (Hardin, 1968), wherein individual incentives to maximize withdrawals coupled with externalized costs of over-use lead users to deplete the resource base and underinvest in necessary infrastructure.
Because it is both difficult to prevent people from using a CPR and because the CPR can be depleted by its use, institutions matter for whether CPRs are sustained over time (Cox et al., 2010; Ostrom, 1990).

Institutions are the rules, norms, and strategies that humans employ to organize economic behavior (Ostrom, 2005). In a self-governance context, these institutions are selected by the CPR users themselves. Rules, which stipulate prescribed, permitted, or prohibited behaviors under threat of prescribed punishment, differ from norms in that norms do not have a prescribed punishment attached to their violation but are instead socially enforced at the discretion of others (Ostrom, 2005). In a poly-centric world with many centers of governance authority (Andersson & Ostrom, 2008; Ostrom, 2010), there are legal and practical limits on rules employed by self-governing irrigation systems, particularly state enforced water rights. Further, there are geographic, economic, and technological factors which constrain and enable water’s movements in a social-ecological system (SES) (Gunderson & Holling, 2002; Ostrom, 2009), potentially shaping rule choice and the influence of rules. Further still, irrigators themselves carry culturally transmitted norms about what one ought and ought not do (Henrich et al., 2005; Ostrom, 2000; Richerson & Henrich, 2009), also potentially shaping rule choice and the influence of rules.

The importance of institutions, particularly rules, suggests that they could be used to achieve climate change adaptation (Huntjens et al., 2012; Kirchhoff & Dilling, 2016). However, while it is clear that rules matter for CPR governance, it is
not sufficiently clear how rules interact with biophysical context, each other, and cultural norms (Ostrom, 2005; Poteete et al. 2010), especially in a highly developed, globalized economy undergoing climate change (Cox, 2014b). These contextual factors are at the core of the panacea problem raised by Ostrom (2007), Ostrom & Cox (2010), and Meinzen-Dick (2007), which still not been fully addressed (Pahl-Wostl et al., 2012). As Meinzen-Dick (2007: 15200) notes (emphasis added):

    The past 50 years of water policy have seen alternating policies emphasize the state, user groups, or markets as essential for solving water-management problems. A closer look reveals that each of these solutions has worked in some places but failed in others, especially when policies attempted to spread them over too many countries and diverse situations. … Research that identifies the critical factors affecting irrigation institutions can lead to sustainable approaches that are adapted to specific contextual attributes.

    In response to the panacea problem, Pahl-Wostl et al. (2012) identify that poly-centric water governance regimes “characterized by a distribution of power but effective coordination structures” (pp 24) perform better than centralized and fragmented regimes in a study of 29 river basins world-wide. And while it may be tempting to deem poly-centricity a new panacea, Pahl-Wostl et al. (2012) identify that the major benefit of poly-centric regimes appears to be their ability to incorporate contextual information in shaping “place-specific responses” (pp 32). This means that policy-makers and irrigators within poly-centric regimes still need to know what are the “critical factors affecting irrigation institutions” (Meinzen-Dick, 2007: 15200) so that it is possible to develop “sustainable approaches that are adapted to specific contextual attributes” (Meinzen-Dick, 2007: 15200). Indeed, for policy-makers and irrigators operating in less favorable governance regimes, it may
be even more important to know what kinds of contextual factors influence the role of rules in affecting irrigation outcomes.

This leads to the overall research question of this dissertation: How do rules interact with context – specifically, biophysical context, other rules, and cultural norms – to influence irrigation performance in self-governing irrigation systems under climate change? To answer this question, this dissertation investigates three essential institutional features of irrigation systems and other long-lived CPR regimes: *de facto* access rights, allocation and distribution rules, and monitoring rules. The contextual factors chosen for investigation were selected for their ubiquity: all long-lived CPR regimes are embedded within a biophysical context, all are governed by more than one rule, and all are accessed by humans who possess norms. By assessing the influence of these rules, under these contextual factors, and during periods of water scarcity and declining water availability, this dissertation seeks to provide a greater understanding of how rules might be used to adapt self-governing irrigation systems to climate change.

The remaining sections of this chapter provide necessary background for the dissertation. First is a presentation of the framework and theory used to address the research question. Next is an explanation of the theoretical propositions and major contribution of the dissertation. Third is a description of the research setting and the specific cases under investigation. The next section is a general overview of the methods of data collection and analysis. Then the chapter details specific
hypotheses and variable measures. Finally, there is a summary of the arguments presented in the subsequent empirical chapters.

1.2. The Institutional Analysis and Development Framework and Common Pool Resource Theory

Because of the institutional nature of the research question, this dissertation employs the Institutional Analysis and Development (IAD) framework to organize data about the study system. In addition to being designed to analyze institutions, the IAD framework is flexible enough to address the different foci of each chapter, can be applied across diverse cases, has well defined and clearly separated variables and concepts, and easily accommodates different theories (Heikkila & Andersson, 2018; Sabatier, 2007).

Figure 1.1 illustrates how the IAD framework is adapted from Ostrom (2005) for the purposes of this dissertation. It is a more applied conceptualization of the specific research problems posed. Figure also 1.1 shows some key variables from CPR theory that are used throughout the dissertation. CPR theory (Cox et al., 2010; Ostrom, 1990) is used to lead preliminary questions, select variables, formulate hypotheses, and check inferences. It is an appropriate choice given its focus on complex human-environment interactions and demonstrated explanatory power in experimental, survey, and field studies (Cox, 2014a; Cox & Ross, 2011; Heikkila, 2004; Heikkila et al., 2011; Ostrom, 2005; Poteete et al., 2010; Smith, 2016, 2018).
Moreover, CPR theory fits the URGB where common property and individual use rights has been maintained, perhaps wisely (Bretsen & Hill, 2006).

**Figure 1.1.** Depiction of adapted IAD framework. Shows how variables relate to each other and generate feedbacks. The figure presents generalized variable concepts. Not included in this figure are variables like population density, soil type, aspect, etc. though these are important and accounted for in specific analyses.

The URGB has a wealth of data, making CPR theory attractive for its ability to incorporate other fields of study relevant to the role of institutions in shaping climate change adaptation of irrigation systems, such as hydrology, ecology, evolution, economics, and behavior. Few study systems have the depth of data available in the URGB due to the role of federal, state, and local agencies in funding data collection and archival. Therefore, biophysical variables, socio-economic
attributes, and institutions can be simultaneously accounted for using multiple measures of variable concepts for validation purposes.

1.3. Theoretical Propositions

The central argument of this dissertation is that the influence of rules on performance depends on context: biophysical variables, other rules, and norms. Demonstrating this is difficult because linking irrigation performance to particular institutional features requires numerous data points and entails great complexity (Cox, 2014a; Lam, 1998; Ostrom, 1992; Poteete et al, 2010; Smith, 2016). Despite the challenges, CPR theory has developed to the point that some predictions can be made about the influence of institutions in context on the performance of self-governing irrigation systems: (1) biophysical variables will dominate irrigation system performance, but institutions by themselves and through interactions with context also greatly influence performance, (2) user-originated rules interact with each other and with biophysical context to influence performance, and (3) cultural groups of distinct historical origins will internalize different norms over time, these norms will be correlated with irrigation system features, and they will interact with user-originated rules to shape irrigation performance. These predictions are explained and refined below.

Property rights are an efficient way of sustaining CPRs (Agrawal, 2013; Grafton et al., 2011; Ostrom, 2005). The de jure water rights regime in the URGB – Prior Appropriation (PA), sometimes summarized as “first in time, first in right”
(Kenney, 2005; Libecap, 2011) – creates a system where irrigators are ranked such that “senior” users may take water prior to and for longer periods than “junior” users. The prevalence of administrative agents and law suits seeking to enforce PA illustrates active enforcement, a critical feature of commons management (Ostrom & Nagendra, 2007). Despite being enforced and observably influential law (Xu et al., 2014a, 2014b), some scholars argue that PA has “died” (Wilkinson, 1991) or been weakened due to federal and state regulations and the ever-increasing costs of enforcement (Benson, 1998, 2012; Tarlock, 2000, 2001). Further, there is a tongue-in-cheek saying in the SLV: “It’s better to be upstream with a shovel than downstream with a water right.” The aphorism highlights that wherever water flows and at whatever scale, those upstream can get the better portion of the flow compared to those downstream (e.g. Turkey and Syria; Mississippi v. Tennessee; see also Janssen et al., 2011 and Lam, 1998). Thus, the number of upstream users (Janssen et al., 2011; Lam, 1998) in addition to physical features such as the watershed area (USDA, 2012b), number of tributary streams (Xu et al., 2014b), and storage access (Cox & Ross, 2011; Schlager et al., 1994; Smith, 2016) ought to influence the relative role of water rights in shaping irrigation outcomes. Furthermore, rights may also be subject to cultural norms and higher level policies. This dissertation tests the argument that in a changing climate the influence of water rights on irrigation outcomes, and therefore their usefulness for adaptation, depends on the biophysical, cultural, and policy context of irrigators.
Beyond water rights, the rules irrigators adopt among themselves for water management are influential for irrigation outcomes (Cox et al., 2010; Janssen et al., 2011, 2012; Lam, 1998). Further, the configuration of rules, not just the presence or absence of discrete rules, matters for outcomes (Baggio et al., 2016), such as equity. The equity of outcomes in a CPR regime are relevant for climate change adaptation (Ingram et al., 2008): unfair outcomes undermine the collective action necessary to maintain CPRs over time and under stress (Arnold, 2008; McCord et al., 2017; Pérez et al., 2016; Poteete et al., 2010). A ubiquitous equity challenge for irrigation systems is the temptation of users upstream on the canal to withdraw excess water and therefore deprive downstream users of a fair share (Janssen et al., 2011, 2012; Lam, 1998). Directly relevant for adapting to water shortage and the equality of upstream and downstream users are two universal institutional features of self-governing irrigation systems: water delivery rules and water allocation rules (Dinar et al., 1997; Joshi et al., 1998; Ostrom, 1992). Rotational delivery is the practice of sending water in turns to individual farmers or groups of farmers. In shortage, rotation has been shown to improve the equality of crop production compared to the simultaneous delivery of water to all farmers at once (Abdullaev et al., 2006; Turrell et al., 2002). Additionally, allowing for flexible allocations of water between farmers in shortage has been shown to improve irrigation outcomes by increasing the marginal productivity of water (He et al., 2012; Torell & Ward, 2010; Ward et al., 2013). Yet how flexible water allocation interacts with rotation has not been directly studied, leaving open the question of how their interaction influences crop
production and its equality. Relevant for climate change adaptation, the outcomes of these rules have not been assessed for their performance as water availability decreases. This dissertation advances the irrigation literature by considering the combined effects of flexible water allocations and rotational delivery on irrigation performance at different levels of water scarcity and at different distances along the length of the irrigation canal.

Finally, increasingly the CPR and cultural evolution literatures utilize Multi-Level Selection (MLS) theory (Creanza et al., 2017; Richerson et al., 2002; Waring et al., 2017; Wilson et al., 2013) to explain institutional evolution, including the evolution of norms. CPR and MLS theory have cognized norms as internalized heuristics of behavior that partly underlie the motivation of boundedly rational actors to cooperate through collective action to sustain a CPR (Carballo et al., 2014; Poteete et al., 2010; Rustagi et al., 2010). MLS theory predicts that selection favors the internalization of competitive norms because competitive individuals maximize their own net benefits (Nowak, 2006). However, cooperative norms can evolve when superior net benefits accrue from actions that benefit others as well as the individual (Nowak, 2006; Ostrom, 2000; Poteete et al., 2010). There are many contextual mechanisms that can differ between groups that select for the internalization and transmission of more or less cooperative norms (Henrich, 2014; Prediger et al., 2011; Talhelm et al., 2014; Tucker & Taylor, 2007). Therefore, irrigation systems founded by different cultural groups with different historical selection pressures may be organized differently to be congruent with their differing
norms (Henrich, 2014; North, 1990). Further, rules and norms interact to influence outcomes (Hoogesteger, 2015; Janssen, 2015; Kamran & Shivakoti, 2013; Ostrom, 2000; Vollan et al., 2013). More competitive groups should become more cooperative in the presence of an enforced rule promoting cooperation (Ostrom, 2000; Rustagi et al., 2010), while more cooperative groups should show the same or decreased cooperative behavior due to crowding-out of norms caused by the enforcement of the cooperation-promoting rule (Kinzig et al., 2013; Rode et al., 2015). This dissertation tests whether norms are associated with the features of irrigation systems and how norms interact with rules during drought using a unique study system, the URGB, comprised of two distinct cultural groups, Hispanic and Anglo, which founded self-governing irrigation systems between the 1670s and 1940s.

1.4. Irrigation and Climate Change in the URGB

1.4.1. Irrigation in the URGB

The study area within the URGB includes the SLV and the Taos Valley of New Mexico (Figure 1.2). The croplands are situated within a high-altitude desert 7,500-8,500 feet above sea level where rural communities irrigate between 350,000-550,000 acres using snowmelt from the surrounding mountains which often exceed 14,000 feet. The economy of the area depends largely on irrigated agriculture, and for many of the people there the struggle to grow crops is existential.
Figure 1.2. Map of irrigation systems surveyed in 2013. From Chapter 4.
Further, because there is no major urban center to demand water in the study area, and because major trans-mountain exports have been made prohibitively expensive by geography and local opposition (Cody et al., 2015), the dynamics of self-governing irrigation systems can be explored without confounding factors. The study area also offers a rich historical and contemporary legal and physical record that makes available a great deal of data, offering multiple measures of conceptual variables and allowing for the isolation of specific variables. Data sources include but are not limited to the U.S. Geological Survey, State of Colorado, State of New Mexico, county governments, and U.S. Census. Finally, the study area overlaps with the closely related work of Cox (2010, 2014a) and Smith (2014, 2016, 2018a), building upon previous insights and data collection.

Especially important for the fourth chapter, but also important for Chapters 2 and 3, are the historical patterns of colonization in the URGB. Spanish colonists, moving South to North, established the *acequia* system of irrigation in the study area around 1670 (Rivera, 1998). *Acequias*, a common property irrigation system, evolved over centuries if not millennia primarily for subsistence purposes (Rodriguez, 2006). Originating in Western Asia and Northern Africa, they were brought to the Iberian Peninsula by the Umayyad Caliphate. *Acequias* were later established in Spanish colonies in the Americas, mingling with subsistence Native American irrigation methods (Hutchins, 1928; Rodriguez, 2006). Market-oriented Anglo-American homesteaders, moving North to South, began to colonize the study area in the 1870s. Cash replaced barter, and banking and insurance entered.
Infrastructure such as rail and large surface reservoirs were also developed. Crucially, under American law, water became de jure private property under PA (Kenney, 2005). Spanish land tenure was also disrupted, instead being allocated using the grid-based Public Land Survey System (PLSS). However, these legal changes did not occur in all areas of the URGB (Table 1.1). Many of the user-originated rules of acequias survived, and to this day irrigators on acequias retain a unique identity. Acequias and Anglo systems therefore allow for tests of hypotheses about the influence of differing cultural norms.

**Table 1.1.** Historical origins and legal context of URGB irrigation systems. The survey sample contains one acequia in Rio Grande County, but is included within Conejos County for simplicity. From Chapter 4.

<table>
<thead>
<tr>
<th>Irrigation System Traits</th>
<th>Taos Acequias</th>
<th>Costilla Acequias</th>
<th>Conejos Acequias</th>
<th>Anglo Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earliest Irrigation</td>
<td>1670s</td>
<td>1850s</td>
<td>1850s</td>
<td>1870s</td>
</tr>
<tr>
<td>Recognition in U.S. Law</td>
<td>1850s</td>
<td>2000s</td>
<td>2000s</td>
<td>1870s</td>
</tr>
<tr>
<td>De Facto Water Rights in Past Between Systems</td>
<td>Repartimiento</td>
<td>Repartimiento</td>
<td>Repartimiento</td>
<td>Prior Appropriation</td>
</tr>
<tr>
<td>De Facto Water Rights in Present Between Systems</td>
<td>Repartimiento</td>
<td>Prior Appropriation</td>
<td>Prior Appropriation</td>
<td>Prior Appropriation</td>
</tr>
<tr>
<td>De Facto Water Rights in Past Within Systems</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Pro-Rata Shares</td>
</tr>
<tr>
<td>De Facto Water Rights in Present Within Systems</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Pro-Rata Shares</td>
<td>Pro-Rata Shares</td>
</tr>
<tr>
<td>Irrigated Land Tenure</td>
<td>Vara Strips</td>
<td>Vara Strips</td>
<td>PLSS</td>
<td>PLSS</td>
</tr>
<tr>
<td>Survey Sample Size (Sole Owners Excluded)</td>
<td>18</td>
<td>12</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Major Crops of Systems in Survey Sample</td>
<td>Alfalfa, Pasture, Gardens</td>
<td>Alfalfa, Pasture, Grain</td>
<td>Alfalfa, Pasture, Grain</td>
<td>Alfalfa, Pasture, Potato, Grain</td>
</tr>
<tr>
<td>Percent of Survey Sample with Reservoir Acess</td>
<td>11</td>
<td>33</td>
<td>44</td>
<td>48</td>
</tr>
<tr>
<td>Irrigation System Hectares in Survey Sample</td>
<td>Min: 8.3</td>
<td>Min: 11.8</td>
<td>Min: 57.7</td>
<td>Min: 34.4</td>
</tr>
<tr>
<td></td>
<td>Median: 69.2</td>
<td>Median: 107.8</td>
<td>Median: 456.8</td>
<td>Median: 1905.2</td>
</tr>
<tr>
<td></td>
<td>Mean: 113.2</td>
<td>Mean: 925.1</td>
<td>Mean: 780.5</td>
<td>Mean: 8192.4</td>
</tr>
<tr>
<td></td>
<td>Max: 558.6</td>
<td>Max: 8036.8</td>
<td>Max: 5806.2</td>
<td>Max: 47475.7</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.: 130.7</td>
<td>Std. Dev.: 2272.5</td>
<td>Std. Dev.: 1302.4</td>
<td>Std. Dev.: 12280.3</td>
</tr>
</tbody>
</table>
1.4.2. Climate Change in the URGB

Recently, the URGB has experienced weather that indicates early signals of climate change. Temperature, frost-free season, onset of peak stream flow, and average annual streamflow have all seen deviations from historical norms (Lukas et al., 2014; Mix et al., 2009, 2011, 2012) in line with climate change expectations (USBR, 2013). Two time periods are important for this dissertation: 1984-2015 and 2011-2014. The first matters because 1984 is the start of the Normalized Difference Vegetation Index (NDVI) time-series which allows for crop growth to be assessed using remote sensing. This time-series ends in 2015 when the data were collected, totaling 32 years of data, greater than the 30-year window necessary to meet the Intergovernmental Panel on Climate Change definition of climate. During this period, annual snowpack declined while annual average temperature increased similar to expected climate changes (Figure 1.3), though not necessarily the result of climate change. The other time period is important because it contains the year of the irrigation leader survey (2013) and was a period of drought (Figure 1.4), allowing for an analysis of conditions analogous to climate change.
Figure 1.3. Annual mean temperature, left panel, and snowpack, right panel, from 1984-2015 of all stations in the SLV with at least 15 years of data. Ordinary Least Squares regression lines of best fit with 95% confidence intervals also shown.

Figure 1.4. Snowpack in the SLV from 2011-2014, showing below normal peak, earlier peak, and earlier melt-out (NRCS, n.d.)
1.5. Analytical Approach and Data Gathering

A mixed-method or multi-method approach combined with careful case selection for natural experiments is increasingly encouraged when research questions cannot be answered using experiments or process modeling, when study systems involve many different kinds of biophysical and social data, and when data is difficult or impossible to acquire or reconcile (Cox, 2015; Poteete et al., 2010). Observational studies such as this dissertation require data about numerous potentially confounding variables, and these data are seldom available at the same unit of analysis or resolution. The URGB overcomes many of these challenges due to the richness of its data and the stability of the units of analysis over time. Table 1.2 shows the hypotheses and summarizes the research conducted for this dissertation, showing the variables used in analysis as well as the data sources.

Table 1.2. Summary of investigation.

<table>
<thead>
<tr>
<th>Research Question</th>
<th>How do de facto access rights interact with contextual factors to affect irrigation performance under climate change?</th>
<th>How do user-originated rules interact with each other and context to affect irrigation performance under climate change?</th>
<th>How do cultural norms interact with the presence of monitoring agents to affect irrigation performance under climate change?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit of Analysis &amp; Sample Size</td>
<td>Irrigation Systems, N = 402</td>
<td>Irrigated Fields, n = 6711</td>
<td>Irrigation Systems, n = 71</td>
</tr>
<tr>
<td>Hypotheses</td>
<td>H1. There is a positive relationship between irrigation performance and higher water right priority. H2. There is a negative relationship between irrigation performance and the number of diversions upstream of a given diversion. H3. There is a positive relationship between</td>
<td>H1. The effect of shortage sharing on irrigation performance depends on how water is being delivered, and the effect of the delivery method on irrigation performance depends on whether shortage sharing is practiced. H2. The effects of shortage sharing and delivery rules on</td>
<td>H1: Hispanic irrigation systems will adopt rules and technologies that promote equality and collective action at higher frequencies than Anglo systems. H2: Where rules are congruent with competitive norms, monitoring agents will reduce water use violations, improve</td>
</tr>
</tbody>
</table>
irrigation performance and catchment size. H4. There is a negative relationship between irrigation performance and diverting from a tributary. H5. The influence of water rights will depend on climate, geography, culture, and higher-level policy.

Average crop production, and decrease crop production equality. H3. Where rules are congruent with cooperative norms, monitoring agents will have no effect or a negative effect on water use violations, decrease average crop production, and increase crop production equality. H4. Where competitive rules are incongruent with cooperative norms, monitoring agents will increase water use violations, reduce average crop production, and reduce crop production equality.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Water Rights</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Priority rank</td>
<td></td>
</tr>
<tr>
<td>Biophysical Variables</td>
<td>- Upstream Rank</td>
</tr>
<tr>
<td>- Catchment Area</td>
<td>- Diverts from a Tributary</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biophysical Variables</th>
<th>User-Originated Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Field Distance from Diversion</td>
<td>- Change Water Allocations</td>
</tr>
<tr>
<td>- Acrefeet Diverted per Acre</td>
<td>- Rotational Water Delivery</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cultural Norms</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Acequia Status</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Higher-Level Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>- County</td>
</tr>
<tr>
<td>- US State</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User-Originated Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Monitoring Agent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Snow Water Equivalent</td>
</tr>
<tr>
<td>- Elevation</td>
</tr>
<tr>
<td>- Majority Sprinkler Irrigated in Majority of Years</td>
</tr>
<tr>
<td>- Percent Years Using a Surface Reservoir</td>
</tr>
<tr>
<td>- Acequia Status</td>
</tr>
<tr>
<td>- Groundwater Access</td>
</tr>
<tr>
<td>- Southern Aspect</td>
</tr>
<tr>
<td>- System Acreage</td>
</tr>
<tr>
<td>- Percent System Area Served by Multiple Irrigation Systems</td>
</tr>
<tr>
<td>- Water District</td>
</tr>
</tbody>
</table>

| Field Acreage | - Days Water is Normally Available |
| Water Right Rank | - Days of Water Available Less than Normal |
| Field Distance to Stream | - Rotation in Scarcity |
| Slope | - Normally Rotate |
| Field Acreage as Percent of Total System Acreage | - Labor Required |
| Historical Percent of the Irrigation System's Maximum Acreage Irrigated | - Inter-System Sharing Arrangements |
| Historical Percent of Average Streamflow | - Groundwater Wells |
| Sprinkler Use | - Vegetable Gardens Present |
| Monitoring Agent | - Change Allocations in Scarcity |
| Sole User | - Percent Hispanic |
| Water Allocated Based on Land Owned or Need | - Water Not Allocated by Private Rights |
| Access to a Reservoir | - Dependency Ratio |
| Days Water is Normally Available | - Hold Annual Meeting |
Additionally, interdisciplinary research requires extensive and careful data selection to ensure both internal and external validity (Cox, 2015; Poteete et al., 2010). Overall, this implies the need for a diverse set of methods and an approach that uses different tools and kinds of data to establish different but necessary lines of evidence in the process of testing a hypothesis or falsifying or supporting a line of argument. In order to produce informative and robust results, this dissertation makes controlled comparisons of irrigation systems that hold constant and account for many relevant causal variables simultaneously. While all empirical chapters
rely on quantitative hypothesis tests using frequentist inferential statistics, especially regression (tested for robustness in each chapter by spatially explicit regression), qualitative data garnered through key stakeholder interviews, archival document review, direct and participant observation, and open-ended survey questions provide necessary ground truthing and assist in interpretation of statistical analyses. Quantitative analysis of survey data is a common practice in social science (Poteete et al., 2010) as is combining quantitative biophysical data and qualitative social data (Cox, 2015).

Chapters 3 and 4 in this dissertation make use of a survey administered in the summer of 2013 to a stratified, semi-random sample of irrigation system leaders based on a quasi-experimental design (Ferraro, 2009). The sample contains 60 irrigation system leaders in the SLV (out of 657 – 9.1%) and 18 in Taos (of 51 – 35.3%), which represents 11.0% of all irrigation systems in the study area. Stratification was performed on groundwater access, water right priority, upstream ranking, irrigated acreage, and *acequia* status (in Colorado). The survey is vital because these leaders were almost always themselves irrigators and interfaced with other irrigators, irrigation system board members and hires, the state’s agents, and other national and local actors of importance. Of any one person on each system, they were able to provide the most detailed and accurate representation of the irrigation system. Although there is always the potential that responses do not reflect real-world conditions, ongoing site visits, publicly available data, and conversations with key informants substantially confirm that the survey responses
reflect reality. Important for the usability of the knowledge produced by this dissertation, the research questions, data collection methods, and results were coproduced with stakeholders through an iterative process of consultation and refinement (Dilling & Lemos, 2011).

Publicly available data sources used in this dissertation are shown above in Table 1.2 and include: the Colorado Department of Natural Resources, which provided a wealth of data on irrigation infrastructure, water rights, historical diversion records, climate, and much more; the New Mexico Office of the State Engineer and Taos County Assessor’s Office, which provided similar data on irrigation systems in New Mexico; the Natural Resources Conservation Service, which provided soil and snowpack data; the US Geologic Survey (USGS), which provided an elevation dataset used to generate many variables such as watershed area, slope, and aspect; the US Census, which provided data on population, age distributions, ethnicity, and home ownership; and GoogleEarth Engine, which made USGS collected NDVI data available without the need to further process the data. Finally, Michael Cox and Steven Smith also shared data from their work in 2010 and 2014, respectively. This was particularly helpful with regards to New Mexico.

1.6. Road Map of the Dissertation

The next three chapters investigate the overall research question of this dissertation: How do rules interact with context – specifically, biophysical context,
other rules, and cultural norms – to influence irrigation performance in self-governing irrigation systems under climate change?

The goal of Chapter 2 (Cody, 2018b) is to better understand how irrigation systems’ externally enforced *de facto* water rights and biophysical, cultural, and policy context interact to generate irrigation outcomes. Using genetic matching and regression methods applied to data covering 402 irrigation systems in Colorado over a 32-year period of climatic conditions similar to those anticipated under climate change, the chapter finds that water rights and watershed area have statistically indistinguishable significant influences on the duration of water diversion, the volume of water diverted, and the overall area systems irrigate. Additionally, the influence of water rights is moderated by the number of upstream diverters, whether the irrigation system diverts from a tributary stream or mainstem river, the watershed area, and snowpack. Cultural norms and higher level policy do not significantly interact with water right priority in this study. This chapter establishes that rules can serve to delimit water availability to irrigation systems and sets the stage for the subsequent chapter, which investigates rules enforced by irrigators on the same system. Further, it highlights the inherent conflict between upstream and downstream irrigators, also explored in the following chapter. Finally, this chapter identifies that water rights can be a source of inequality (and, conversely, equality), particularly in physical water shortage.

The purpose of Chapter 3 (Cody, 2018a) is to better understand how the rules irrigators use to manage water among themselves on the same irrigation system
influence irrigation outcomes. Of particular interest in this chapter is the inherent conflict between upstream and downstream irrigators and the rules they use to mitigate this conflict to ensure ongoing collective action and crop production. In contrast to the previous chapter where, due to government agents, financing, and courts, irrigation systems did not depend on extensive collective action between each other for their continued existence, irrigators using the same common property canal system need to ensure ongoing collective action to maintain infrastructure and prevent rampant water use violations. Using a four-year drought and a sample of 6,711 individual irrigated fields nested within 60 irrigation systems in Colorado, this chapter uses regression methods to investigate how two rules, rotational water delivery and flexible water allocations, influence crop growth along the length of an irrigation canal and at different levels of water availability. The chapter finds that the presence of both rotational water delivery and flexible water allocations equalize crop production between upstream and downstream irrigators regardless of water availability. The marginal productivity of water, i.e. the additional crop produced for each additional unit of water, is also equalized between upstream and downstream irrigators on systems using this combination of rules. However, other configurations of these rules outperform rotation with flexible allocations for upstream and/or downstream users at some levels of water availability. These results highlight the contextual influence of rules and raise important questions about the role of monitoring and equality in maintaining cooperation between irrigators in scarcity. These themes are explored in the fourth chapter.
The objective of Chapter 4 is to better understand the role of norms in influencing the form and function of self-governing irrigation systems. Covering four years of drought, this chapter analyzes surveys of 71 systems in Colorado and New Mexico arising from distinct cultural origins and histories. Using hierarchical cluster analysis and regression methods viewed through the lens of CPR and MLS theory, it assesses how features of irrigation systems correlate with norms and how extant norms influence irrigation outcomes under the presence or absence of a monitoring agent. As to the form of self-governing irrigation systems, results show that cultural norms and higher-level policies (such as property rights) are significantly associated with the rules and technologies adopted by irrigation systems. As to the function of self-governing irrigation systems, norms moderate the influence of a monitoring agent on the frequency of water use violations, the average level of crop production, and the equality of crop production. Notably, monitoring agents that enforce rules which are incongruent with cultural norms are associated with increased water use violations and lower average crop production than comparable systems without a monitoring agent. This chapter highlights the importance of rules, norms, and technology as co-evolving features of a CPR regime that need careful attention when considering changes to policy, investments, and cultural exchange.
1.7. Chapter Conclusion

As self-governing irrigation systems come under worsening water stress as a result of population growth and climate change (UNESCO, 2012), institutional changes may be employed to adapt (Huntjens et al., 2012; Kirchhoff & Dilling, 2016). However, “one-size-fits-all” policy prescriptions and panaceas have been insufficient or harmful in many contexts (Meinzen-Dick, 2007; Ostrom & Cox, 2010), and even broader recommendations such as the adoption of poly-centric governance regimes seem to work largely because of their ability to tailor specific policies to local context (Pahl-Wostl et al., 2012). Therefore, this dissertation focuses on the role of context in shaping irrigation performance. Using publicly available data combined with a stratified survey of self-governing irrigation system leaders in a region undergoing weather patterns analogous to climate change, this dissertation tests several hypotheses about three essential institutional features of long-lived CPR regimes – de facto access rights, allocation and distribution rules, and monitoring rules – in relation to three ubiquitous contextual factors: biophysical context, other rules, and cultural norms. The results of this dissertation will help academics, water managers, and irrigators to better understand the policies that will be more likely to be effective in responding to climate change.
2.1. Chapter Summary

One of the major challenges facing water management around the globe is the interaction between upstream and downstream water users. In theory, water rights should be an effective way to mitigate the “stationary bandit” behavior of upstream users (Janssen et al., 2011). But are they in practice? And to what degree does climate change influence upstream-downstream relationships when water rights are involved? To address these questions, this study looks at irrigation performance in the Rio Grande Basin in Colorado, commonly referred to as the SLV, where snowmelt dependent irrigation is the dominant economic activity. Like other regions of the world, the SLV hosts informally and formally enforced water rights, multiple watersheds with differing physical, cultural, and policy environments, and hundreds of irrigation systems with a wide range of attributes. Importantly, the SLV has ample public data on geography, hydrology, climate, and irrigation systems, offering a chance to control for effects that might be difficult to engage elsewhere.
At a minimum, an irrigation system is defined as the physical infrastructure used to capture, divert, and deliver water to the fields of irrigated farmers (Ostrom, 1992). In studies of irrigation systems, the users of the system as well as the lands irrigated by the system are also covered by the phrase “irrigation system” (Cox & Ross, 2011; Lam, 1998; Ostrom, 1992). To say that these irrigation systems are user-governed means that farmers themselves maintain and manage the distribution of water through the headgates, canals, and ditches (Mabry, 1996).

Irrigation performance in this study is measured at the level of the irrigation system (not individual farmers), and is assessed by three metrics for each year of the study period (1984-2015): the percentage of irrigable land irrigated by a given system, the percentage of the maximum volume of water diverted by a given system over the study period, and the number of calendar months over the calendar year during which water was diverted by a given system. See Section A2.1 of Appendix A for more information on irrigation performance.

Irrigation performance is important for global food security, a growing problem that will be made worse as the climate changes and demands on water resources grow (Castex, et al., 2015; Cox, 2014a; Fernald et al., 2012; Hurlbert & Mussetta, 2016; Wheeler & von Braun, 2013). Irrigation of crops is responsible for 40 percent of the world’s food supply and is expected to provide most new food (UNESCO, 2012). Climate change threatens the water supply to many irrigation systems (FAO, 2012; Gleick, 2003), and therefore global food security. Because approximately three quarters of irrigated cropland and one quarter of all cropland
relies on small-scale, user-governed irrigation systems worldwide (Mabry, 1996), adaptation will be performed primarily by farmers. In this context, user-governed irrigation systems' adaptations result in varying irrigation performance (Cox & Ross, 2011; Janssen & Anderies, 2013). Performance depends on the interactions between geography, technology, and institutions (Hansen et al., 2011; Ostrom, 1992; Poteete et al., 2010).

One way that irrigators might be able to adapt to climate change is through the adoption and adaptation of property rights to water (Gupta & Lebel, 2010; Meinzen-Dick, 2014). Research on human behavior indicates that both moral and economic incentives can influence collective action (Ostrom, 2005). Institutions such as water rights provide both economic and moral information to water users, and therefore institutions should be influential in determining irrigation performance because of their capacity to reveal information about the potential economic and social outcomes of alternate decisions. While the water rights regime in Colorado – Prior Appropriation (PA) – is unique to the Western US, some portions of Canada, and Australia, the ultimate effect of the regime is to create a “priority system” where irrigators are ranked based on a rule of “first capture” (Kenney, 2005; Libecap, 2011) and higher ranking “senior” users may take water prior to and for longer periods than “junior” users, who sometimes receive no surface water at all. Property rights in the United States generally and water rights in Colorado especially are strongly enforced by the court system, and so one would expect
property rights to water to dominate irrigation in the SLV and in other contexts of strong enforcement.

However, there is a tongue-in-cheek saying in the SLV: “It’s better to be upstream with a shovel than downstream with a water right.” The aphorism highlights the importance of being able to divert water before other irrigators and thus deprive them of water. Similarly, in an extensive study of irrigation performance in Nepal, Lam (1998) finds that on irrigation systems themselves, upstream users (“head-enders”) tended to access water more reliably than downstream users (“tail-enders”). At a larger scale, downstream nations (e.g. Mexico, Egypt, Vietnam) also often find themselves in less powerful positions relative to their upstream counterparts (The United States, Ethiopia and Sudan, China, respectively). Between US states, many lawsuits brought between states over water involve the downstream state suing the upstream state for allegedly taking more than its fair share (e.g. Texas v. New Mexico and Colorado; Florida v. Georgia; Mississippi v. Tennessee). Experiments find that upstream users act as “stationary bandits”, depriving downstream users of water (Janssen et al., 2011; Lam, 1998).

That said, in a snowmelt driven system, being too far upstream is hypothetically possible. If diverting from a tributary rather than a mainstem, fewer streams aggregate and therefore reduce the reliability of flow (Xu et al., 2014b). And if catchment sizes are smaller, less water is available (USDA, 2012b). There are instances in Colorado where upstream users have senior rights but are not able to
divert water because it simply is not there (denoted as a “futile call”). Therefore, the hydrograph of the stream from which water is diverted (USDA, 2012b; Xu et al., 2014b), the number of irrigators diverting water upstream of a given user (Janssen et al., 2011; Lam, 1998), and available storage technology (Cody et al., 2015; Cox & Ross, 2011; Smith, 2016) combine to influence physical water availability and therefore the relative role of water rights.

The literature has not come to agreement on the question of whether water rights or geography have more influence on irrigation performance and why that might be (Poteete et al., 2010). Here I look at the effect of water rights and position on the stream, controlling for important variables such as elevation, across a variety of watersheds where conditions are likely to be different in important ways (Alcon et al., 2014). This analysis can inform the kinds of institutional interventions or support, if any, might be needed to adapt to a dryer climate and the some of the important contextual factors that could be involved (Mukhtarov et al.; 2015). At a minimum, it will illuminate the extent to which water rights may be a lever of adaptation to drought.

I evaluate five hypotheses, shown in Table 2.1. In general, I would expect these hypotheses to be true in any snowmelt dependent irrigation context, with the caveat that it is possible some factors – such as treaties and cultural norms – could create situations where these hypotheses do not hold. These hypotheses are evaluated for the period 1984-2015 on a completely sampled population of 696 irrigation systems, drawing on publicly available data collected from the State of
Colorado and the US Geological Survey. To ensure the sample has comparable observations, I use genetic matching procedures (Diamond & Sekhon, 2013; Ho et al., 2007) to produce a final dataset of 402 irrigation systems. Because the variables of interest, water right priority and geographic factors, are time-invariant making fixed-effects analysis impossible, the time-variant data associated with each observation are averaged over the study period. To ease interpretation of results, the data are then standardized (variables are centered at their means, then divided by the variable’s standard deviation) except for the dichotomous and categorical variables. Regression analyses are then performed on this standardized cross sectional data following Gujarati & Porter (2009). Quantitative data and results are complimented by field visits over the period of 2012-2016. The methods section below elaborates this approach, and further details are contained in Section A2.2-A2.3 of Appendix A.

**Table 2.1.** The five hypotheses with their essential rationales and some citations supporting the hypotheses.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Rationale</th>
<th>Citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1. All else equal, there is a positive relationship between irrigation performance and higher water right priority.</td>
<td>Senior rights lead to a longer duration of water availability and more reliable water supply.</td>
<td>Cody et al., 2015; Kamran &amp; Shivakoti, 2013; Kenney, 2005; Libecap, 2011; Smith, 2016; Torpey-Saboe, et al., 2015; Xu et al., 2014a, 2014b</td>
</tr>
<tr>
<td>H2. All else equal, there is a negative relationship between irrigation performance and the number of diversions upstream of a given diversion.</td>
<td>The more irrigators upstream of a given user the larger the chance of over-depletion.</td>
<td>Janssen et al., 2011; Janssen &amp; Anderies, 2013; Kadirbeyoglu &amp; Ozertan, 2015; Lam 1998; Meinzen-Dick, 2007; Zwart &amp; Leclert, 2010</td>
</tr>
<tr>
<td>H3. All else equal, there is a positive relationship between irrigation performance and catchment size.</td>
<td>Smaller catchments have less snowpack, which leads to lower stream flow and shorter durations of water availability.</td>
<td>Lam 1998; USDA, 2012b</td>
</tr>
<tr>
<td>H4. All else equal, there is a negative relationship between irrigation performance and diverting from a tributary.</td>
<td>Tributaries aggregate flows from fewer streams and are therefore have higher flow variability.</td>
<td>Lam 1998; Xu et al., 2014b</td>
</tr>
</tbody>
</table>
Results indicate that while water right priority rank has a significantly positive effect for all dependent variables, its influence depends on several factors, including catchment area, whether the system diverts from a tributary, available precipitation, and number of upstream diversions. Overall, increasing catchment area is as influential as water right priority rank. Other signals are not as strong. Diverting from a tributary is significantly harmful for percent maximum volume diverted and percent area irrigated, but not months of active diversion. Many upstream diversions is only significantly harmful for percent maximum volume diverted. Finally, PA created stark inequalities among irrigators in the extreme 2002 drought, especially among those lacking storage, with senior users receiving their full allocation of water (albeit for a shorter period than normal) and junior users receiving no water. In a context without savings, insurance, credit, and/or access to secondary sources of income or food, PA could generate significant social discord, potentially leading to hunger, migration, and/or physical conflict.

2.2. Theoretical Approach

The IAD framework (Poteete et al., 2010) is useful for examining the question of how the institutional and physical dimensions of a SES interact to influence irrigation performance. In addition to being designed to analyze institutions, the
IAD framework has well defined and clearly separated variable concepts and easily accommodates different theories (Sabatier, 2007). The IAD framework separates contextual variables into three categories: Biophysical, Institutional, and Socio-Economic (i.e. “attributes of the community”). These contextual variables influence actors who make decisions in an “Action Arena”, which produce outcomes that feedback on the contextual variables. Furthermore, related scholarship (Cox, 2010, 2014; Cox & Ross, 2011; Smith, 2014) uses the IAD framework as a basis for investigations into similar questions in geographically proximate and institutionally similar systems. This study complements this work using similar methods. Figure 2.1 illustrates a highly simplified version of the IAD framework and where the variables under consideration fit into it. Figure 2.1 is more applicable to my specific research problem because it locates the variables in physical space. Although there are feedbacks over time in any SES, Figure 2.1 omits them because the variables under consideration here are largely unresponsive to these feedbacks over the study period because they are either legally, financially, or physically limited.
The theoretical relationships between the key variables in a single irrigation season are shown in a modification of the IAD framework (Ostrom, 2005).Normally, IAD considers Context, an Action Arena, Outcomes, and Evaluative Criteria. Here, context has been simplified to Physical Context; Irrigation System Attributes are the Action Arenas; Outcomes are represented by Irrigation Performance; and Evaluative Criteria have been omitted. The variables in italics are those of primary interest to the hypotheses.

Closely related to the IAD framework is CPR theory (Ostrom, 2005), which posits that human users of CPRs can act collectively to create institutions which evolve over time to manage their use of said CPRs and that long-lived commons management regimes share essential features related to the evolution of cooperation (Wilson et al., 2013). Irrigation systems, like all CPRs, face problems with difficulty of exclusion (access to the resource is difficult to restrict) and subtractability (the resource is consumed and made unavailable to others) (Poteete et al., 2010). CPR theory focuses on complex human-environment interactions and
has explanatory power in experimental, survey, and field studies of irrigation (Ostrom, 1992, 2005; Poteete et al., 2010). Moreover, I use CPR theory to lead preliminary questions, select variables, formulate hypotheses, and check inferences.

### 2.3. Climate Change and Irrigation in the SLV

Climate change is expected to negatively affect irrigated agriculture, especially in arid regions reliant on snowmelt (Gleick, 2003; Vicuña et al., 2012; Villamayor-Tomas, 2012; Wheeler & von Braun, 2013). Climate change does this through increases in temperature and therefore crop water demand (potentially offset by CO$_2$ fertilization [Deryng et al., 2016]), and in arid areas through decreases in precipitation (Lukas et al., 2014). Combined, temperature and precipitation changes mean that snowmelt timing and volume are also changed, increasing the challenge for irrigators whose crops rely on snowmelt as opposed to rain, such as those in the SLV. Spring snowpack is decreasing in volume and melting earlier in the SLV and across Colorado due to increasing temperature and dust on snow, with decreasing stream flow in the Rio Grande basin especially (Lukas et al., 2014). Indeed, there have already been observed changes in temperature, and therefore frost-free season, growing degree day patterns, and onset of peak stream flow (Mix et al., 2009, 2011, 2012). That said, increasing temperatures can extend the growing season, a historical limitation in the SLV, especially for high elevation farms. However, earlier snowmelt will complicate the potential benefits of an extended frost-free period, in that it will produce a longer
period over which irrigators will need to rely on surface reservoir storage or groundwater, especially later in the season. If storage water can be accessed, farms will likely see net benefits from increased temperatures.

Regardless of the pace of climate change and what might happen in the SLV long term, drought – defined by lower than average water availability – is harmful for irrigators and will continue to threaten irrigation. Important for this analysis, in 2002 the SLV experienced the worst drought on record, and perhaps in the past 500 years (Woodhouse et al., 2012). The subsequent years have also been unusually dry. Irrigated acreage in 2002 was reduced 40% from 1997 levels. The Rio Grande carried 24% the annual average daily flow at its most important gage in 2002. Most critically, there was no snowmelt after May in 2002 during peak crop water demand (Cody et al., 2015). This drought and the subsequent arid decade can be used to assess the role of water rights and geography under different climatic conditions. See Section A1.3 in Appendix A for more details on climate change in the SLV.

2.4. Water Rights, Management, and Norms in the SLV

The following section describes the water rights regime, how the state administers water in the SLV, and relevant historical factors that influence water allocations. Establishing, monitoring and enforcing property rights have been shown to be an efficient way of sustaining CPRs in theory (Ostrom, 2005), through markets (Grafton et al., 2011), and using case studies (Agrawal, 2013). However, there is disagreement over their influence, given that de jure rights may not in fact
be honored and that geographic and technological factors are also highly influential (Kadirbeyoglu & Ozertan, 2015; Meinzen-Dick, 2007; Ostrom, 1992). Additionally, without mechanisms to quantify and monitor withdrawals from a CPR as well as sanction violators, access rights to that CPR may not be effective from a practical standpoint (Torpey-Saboe, et al., 2015). The SLV offers a chance to study the influence of property rights due to the similarities and differences in how water rights are applied within the SLV. Different watersheds have different historical water rights regimes and different obligations with regards to the Rio Grande Compact (RGC), which together may influence the administration of water rights.

2.4.1. Water Rights: Prior Appropriation

Over 150 years ago, American farmers in the Western United States adopted the Doctrine of Prior Appropriation in water rights. When the irrigation systems were founded, those systems that first began using water beneficially retained a priority right to the water over those who diverted water at a later time (Kenney, 2005). PA is often summarized as the principle of “first in time, first in right”. In practice, this is a non-injury principle, whereby no junior water user – one with a lower priority – may impinge on the full exercise of the water right held by any senior water user – one with a higher priority. Thus, on a given stream system, denoted in Colorado as a Water District (WD), the oldest water right receives its full allocation of water as long as it physically can, while more junior systems may not receive their full allocation, or any water at all, depending on streamflow and the
rights of others. Additionally, the maximum volume that can be diverted by a given irrigation system at a given time is limited by the water rights held by that system. This diversion rate (given in cubic feet per second) was determined at the time the right was claimed, limited by statute to the amount that could be beneficially used for irrigation, a precaution to avoid waste (Kenney, 2005). The maximum diversion rate of the water right, therefore, does not usually influence irrigation performance as it is measured in this study since the maximum diversion rate represents an appropriate amount for the land.

Importantly, the water rights regime is informally enforced by farmers themselves and formally enforced by state agents. PA therefore poses real limits to use (Torpey-Saboe, et al., 2015). Recent studies have found that PA is influential today and is expected to be influential under climate change on the Snake River in Idaho (Xu et al., 2014a, 2014b). Ongoing activity in Colorado’s Water Courts implies that adherence to these water rights is expected by irrigators and consequences follow from a lack of implementation and violations of the law. Private rights to water are culturally important among irrigators and are part of the platform of the Republican Party (Goldstein & Hudak; 2017). Finally, irrigators report that priority administration is the cornerstone of water management in the SLV.

Water right priorities are implemented in real time at the diversion structure of the irrigation system; the point at which the water leaves the natural course of the stream and enters a man-made channel. Once in the channel, priority is essentially irrelevant except in circumstances where more than one water right
priority exists. To manage the water once it is diverted, irrigation systems in the SLV exhibit a range of institutional formality; from completely unwritten oral governance traditions to non-profits with articles of incorporation, bylaws, and shareholders (almost always the irrigators using the canal system, except in the case of absentee land owners). In instances where shares are used to allocate water on the irrigation system, the water rights themselves can be transferred to the corporation, giving farmers the rights to use the amount of water represented by their shares, which can be bought and sold. When water rights are not transferred to a ditch company, they are retained on the deeds to the lands which may be irrigated by the ditch or ditches in question. Although this ditch-level management is interesting, it is beyond the scope of this paper because these factors will have no influence on the duration or volume of water diversion, and only marginal influence on the acreage irrigated.

2.4.2. Water Management: Rio Grande Compact, Water Districts, and Closed Basin

Below I describe key features of the eight WDs in the SLV. Despite PA’s place in the Colorado Constitution, there are open questions in the literature as to whether PA influences irrigator behavior given the host of new environmental regulations, government agencies, interstate agreements, technological interventions, court rulings privileging the public interest, and the costs associated with monitoring and enforcement of water rights (Benson, 1998, 2012; Tarlock, 2000, 2001). In the SLV, the RGC is one such obstruction to PA. Because of the
peculiarities of how the RGC is administered, the state line with New Mexico acts as a kind of “super-senior” that is always owed water, with the amount varying depending on the level of the river at an upstream gage (Paddock, 2013). The amount owed is divided between the Rio Grande (WD20) and Conejos River (WD22), meaning these two stream systems always have water flowing to their respective terminus. Because only these two of the eight WDs in the SLV are covered by the Compact (WD20 and WD22), it will be possible to determine how influential water rights are despite the enforcement of the RGC by comparing the influence of water rights across the different WDs. Table 2.2 shows how the WDs compare across several key variables of interest in this study.

**Table 2.2.** Descriptive statistics of some key variables of WDs and the irrigation systems and counties associated with them. The exact median farm size was not available from the US Department of Agriculture (USDA, 2014), however the data gave a range which contained the median.

<table>
<thead>
<tr>
<th>Water District Features</th>
<th>Water District 20</th>
<th>Water District 21</th>
<th>Water District 22</th>
<th>Water District 23</th>
<th>Water District 24</th>
<th>Water District 25</th>
<th>Water District 26</th>
<th>Water District 27</th>
<th>Water District 35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Stream</td>
<td>Rio Grande</td>
<td>Alamosa-La Jara</td>
<td>Conejos River</td>
<td>Culebra Creek</td>
<td>San Luis Creek</td>
<td>Saguache Creek</td>
<td>Carnero Creek</td>
<td>Trinchera Creek</td>
<td></td>
</tr>
<tr>
<td>Water District Acreage</td>
<td>1.60x10^6</td>
<td>325,481</td>
<td>496,485</td>
<td>456,715</td>
<td>515,552</td>
<td>536,894</td>
<td>165,188</td>
<td>273,930</td>
<td></td>
</tr>
<tr>
<td>Stream Fully Consumed</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Within Closed Basin</td>
<td>Partial</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Partial</td>
<td></td>
</tr>
<tr>
<td>Rio Grande Compact</td>
<td>Must Deliver Water</td>
<td>Non-Tributary</td>
<td>Must Deliver Water</td>
<td>Non-Tributary</td>
<td>Closed Basin</td>
<td>Closed Basin</td>
<td>Closed Basin</td>
<td>Non-Tributary</td>
<td></td>
</tr>
<tr>
<td>Number of Ditch Systems</td>
<td>193</td>
<td>75</td>
<td>105</td>
<td>63</td>
<td>91</td>
<td>106</td>
<td>35</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Average Ditch System Acreage</td>
<td>1761.2</td>
<td>1089.6</td>
<td>1035.4</td>
<td>427.5</td>
<td>397.8</td>
<td>256.0</td>
<td>375.2</td>
<td>1389.1</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
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<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>Percent Ditch Systems Hispanic</td>
<td>6.4</td>
<td>35.7</td>
<td>43.3</td>
<td>43.3</td>
<td>0</td>
<td>0</td>
<td>15.6</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>Percent Ditch Systems with Wells</td>
<td>21.76</td>
<td>57.3</td>
<td>37.1</td>
<td>9.5</td>
<td>30.8</td>
<td>24.5</td>
<td>40.0</td>
<td>28.6</td>
<td></td>
</tr>
<tr>
<td>Percent Ditch Systems with Reservoir</td>
<td>26.4</td>
<td>4.0</td>
<td>52.4</td>
<td>4.8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Percent Ditch Systems Using Tributary</td>
<td>30.6</td>
<td>13.3</td>
<td>5.7</td>
<td>73.0</td>
<td>68.1</td>
<td>24.5</td>
<td>2.9</td>
<td>82.1</td>
<td></td>
</tr>
<tr>
<td>Average Ditch System Catchment Acreage</td>
<td>309,598</td>
<td>121,004</td>
<td>216,159</td>
<td>45,565</td>
<td>35,411</td>
<td>222,208</td>
<td>54,000</td>
<td>58,555</td>
<td></td>
</tr>
<tr>
<td>Major Counties</td>
<td>Alamosa &amp; Rio Grande</td>
<td>Conejos</td>
<td>Conejos</td>
<td>Costilla</td>
<td>Saguache</td>
<td>Saguache</td>
<td>Saguache</td>
<td>Alamosa &amp; Costilla</td>
<td></td>
</tr>
<tr>
<td>County Number of Farms 2012</td>
<td>322; 377</td>
<td>605</td>
<td>605</td>
<td>251</td>
<td>277</td>
<td>277</td>
<td>277</td>
<td>322; 251</td>
<td></td>
</tr>
<tr>
<td>County Median Farm Acreage Range 2012</td>
<td>140-179; 140-179</td>
<td>100-139</td>
<td>100-139</td>
<td>70-99</td>
<td>260-499</td>
<td>260-499</td>
<td>260-499</td>
<td>140-179; 70-99</td>
<td></td>
</tr>
<tr>
<td>County Mean Farm Net Income 2012</td>
<td>$69,445; $88,198</td>
<td>$18,200</td>
<td>$18,200</td>
<td>$23,436</td>
<td>$1.0x10^5</td>
<td>$1.0x10^5</td>
<td>$1.0x10^5</td>
<td>$69,445; $23,436</td>
<td></td>
</tr>
</tbody>
</table>
Further distinguishing the WDs, there is an endorheic basin the SLV called the Closed Basin, into which the streams in the North of the SLV drain (Thiros et al., 2010). This water never reaches the Rio Grande via the surface, and instead recharges groundwater in the unconfined aquifer from which many irrigators in the SLV withdraw, indirectly decreasing the flow of the Rio Grande (Cody et al., 2015). Throughout the modeling process groundwater access is accounted for using a dummy variable indicating whether any land within the service area of the irrigation system is irrigated using groundwater. These Northernmost WDs (WD25, WD26, and WD27) are not administered as part of the RGC (Paddock, 2013). There are many endorheic basins in the Western United States and the world, and PA is applied in the same way in closed and open basins: first in time, first in right. The meaningful difference in the SLV is that this Closed Basin is not administered as part of the RGC, a factor I account for in the models using WD as a factor variable. The remaining three WDs (WD21, WD24, and WD35) have streams that are considered by the State Engineer to have historically not reached the Rio Grande, and are therefore deemed “non-tributary” to the Rio Grande, and thus are also not administered as part of the RGC (Paddock, 2013). See Figure 2.2 for a map of the WDs and the approximate Southern boundary of the Closed Basin.
2.4.3. Cultural Norms: Hispanic and Anglo Irrigation

In addition to the differing hydrology and higher level policies of the WDs, there are differences in historical practices and cultural norms surrounding water allocation between them. PA was not the first water rights regime in the SLV. American settlers were preceded by 20-30 years by the Spanish in the Southern portions of the valley (Rivera, 1998; Rodriguez, 2006), especially in WD21, WD22, and WD24. These irrigators followed a different allocation mechanism, inherited from the Moorish occupation of Spain, whereby a rotational sharing arrangement, a repartimiento, was negotiated among the different acequias, or ditch systems, each year before irrigation began. The farmers, or parcientes, would also negotiate
sharing arrangements between each other on a given acequia (Cox & Ross, 2011; Cox, 2014a). When water was especially scarce, only the best lands were irrigated and the produce shared among the families in the community. Historically distinct from the American system, water was considered public property, it was allocated based on need, and decisions were made using a one-landowner-one-vote system. Many of these ditch-level traditions still apply to the Hispanic irrigation systems that exist today, though there is an ongoing coevolution of ditch-level operations between Hispanic and Anglo systems. Acequias have been slower to adopt high capacity groundwater wells, viewing them as an imposition on their neighbors’ rights to the water they share. It is also the case that the acequias, especially since World War II, have been reluctant and sometimes unable to integrate into the capital market, adopt sprinkler irrigation, and enroll in government farming programs. Acequias are generally smaller, limiting their total productive capacity. However, acequias tend grow a greater diversity of crops, have better maintained soil, a higher water table, require less expensive machinery, use animal fertilizers, and apply fewer chemical pest and weed controls to their land. To account for these factors in the modeling, acequia status is included as a dummy variable, determined by whether the irrigation system has a Hispanic name (e.g. la del rio, Salazar ditch, acequiacita, etc.).

Despite these differences, the Anglo and Hispanic systems are fundamentally similar: they divert water from a stream and bring it to farmland through a gravity fed network of canals and ditches. Crucial for this investigation, both types of
system are treated the same by the state at the point of diversion. Over time, the Americans have, more or less successfully, forced the private water rights regime of PA onto the Spanish customary rights (Rivera, 1998; Rodriguez, 2006). However, while acequias nominally follow PA, the acequia community in Colorado does not openly discuss whether they follow PA, their traditional repartimiento system, or some hybrid of the two. This study should be able to detect any differences in the influence of PA among the acequias by interacting this variable with water right priority. Comparisons between acequias and the Anglo systems allow for transferability of results and illustrate how water rights interact with different historical origins. Many globally relevant systems host distinct but coevolving property rights regimes, sometimes imposed by colonial powers (Kamran & Shivakoti, 2013; Mukhtarov, et al., 2015; Tang & Gavin, 2015).

2.5. Materials and Methods

Careful case selection for “natural experiments” is increasingly encouraged when research questions cannot be answered using laboratory or similar experiments or modeling, when study systems involve many different biophysical and social data, and when data are difficult or impossible to acquire or aggregate (Poteete et al., 2010). Natural-experiments such as this study require data about numerous potentially confounding variables, and these data are seldom available at the same unit of analysis or resolution. However, the SLV overcomes many of these challenges due to the richness of its public data, the stability of the units of
analysis, and four years of site visits by the author to ground truth the data and analysis.

2.5.1. Data Collection and Variable Development

Data were collected from various public sources, primarily the Colorado Department of Natural Resources’ Decision Support Systems and Google Earth Engine. Time-variant data from 1984-2015 were collected for monthly snowpack, monthly temperature, annual stream flow, amount of water diverted by irrigation systems each month, and acres irrigated each year. Time-invariant data such as diversion location, groundwater access, irrigated area, elevation, water right priority, and catchment area were also collected from these public sources.

Variables used in the analysis were selected based on their influence on irrigation performance in preliminary analyses, including: correlations, pair-wise regressions, and ANOVA. Variables such as the number of water rights, the total volume of water rights, latitude, aspect, slope, temperature, and year the irrigation system was founded were evaluated for their influence on irrigation performance and included in preliminary analyses. However, these variables were not deemed sufficiently explanatory or produced unacceptable multicollinearity. Variables included in the analysis are indicated in Table 2.3. See Table A.1 in Appendix A for more information on variable development and measurement.
Table 2.3. Table showing variable included in the analysis, their shorthand name, and their form.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shorthand Name</th>
<th>Variable Type</th>
<th>Variable Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Independent Variables (directly relevant to the hypotheses)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Right Priority Rank</td>
<td>PRIORRANK</td>
<td>Ordinal</td>
<td>Rank</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>UPRANK</td>
<td>Ordinal</td>
<td>Rank</td>
</tr>
<tr>
<td>Diverts from a Tributary Stream</td>
<td>TRIB</td>
<td>Binary</td>
<td>None</td>
</tr>
<tr>
<td>Catchment Area of the Diversion Structure</td>
<td>CATCHAREA</td>
<td>Continuous</td>
<td>Acres</td>
</tr>
<tr>
<td><strong>Control Variables (important for the outcomes but not directly relevant to the hypotheses being tested)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow Water Equivalent at Nearest SNOTEL</td>
<td>SWE</td>
<td>Continuous</td>
<td>Inches</td>
</tr>
<tr>
<td>Elevation of Diversion Structure</td>
<td>ELEV</td>
<td>Continuous</td>
<td>Meters</td>
</tr>
<tr>
<td>Majority Sprinkler Irrigated in Majority of Years</td>
<td>SPRINK</td>
<td>Binary</td>
<td>None</td>
</tr>
<tr>
<td>Percent Years Accessing Surface Reservoir</td>
<td>RES</td>
<td>Percentage</td>
<td>Percentage</td>
</tr>
<tr>
<td>Acequia Status</td>
<td>ACEQUIA</td>
<td>Binary</td>
<td>None</td>
</tr>
<tr>
<td>Acreage of Irrigation System</td>
<td>AREA</td>
<td>Continuous</td>
<td>Acres</td>
</tr>
<tr>
<td>Groundwater Access</td>
<td>GROUND</td>
<td>Binary</td>
<td>None</td>
</tr>
<tr>
<td>Percent Area Served by Multiple Ditch Systems</td>
<td>PERMULITI</td>
<td>Percentage</td>
<td>Percentage</td>
</tr>
<tr>
<td>Water District of Diversion Structure</td>
<td>WD</td>
<td>Categorical</td>
<td>None</td>
</tr>
</tbody>
</table>

**Dependent Variables (outcomes being evaluated)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shorthand Name</th>
<th>Variable Type</th>
<th>Variable Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months of Diversion Activity</td>
<td>MDA</td>
<td>Continuous</td>
<td>Months</td>
</tr>
<tr>
<td>Percent Maximum Diversion</td>
<td>PMD</td>
<td>Percentage</td>
<td>Percentage</td>
</tr>
<tr>
<td>Percent Maximum Irrigated Area</td>
<td>PMIA</td>
<td>Percentage</td>
<td>Percentage</td>
</tr>
</tbody>
</table>

To process the data, I first eliminate observations with missing data, reducing my observations from 694 to 639. Observations were excluded because variables were missing in the state database and the ArcGIS 10.4 was unable to compute watershed areas for some observations. I then use a genetic matching algorithm to ensure my dataset has comparable observations and to reduce model dependence (Diamond & Sekhon, 2013; Ho et al., 2007). This reduces my dataset from 639 irrigation systems to 402. To ease the interpretation of results, I then standardize the data by mean-centering each variable and dividing each variable by its standard deviation (except the dichotomous and categorical variables). See
Section A2.3 in Appendix A for more information on data processing, including a full description of the matching procedure.

There are some limitations to the data. For example, the study lacks any direct data on the wealth available to irrigation systems. However, the area of irrigation systems is a proxy for the total wealth available to that system. As the size of an irrigation system increases, the wealth available to that system for maintenance and operations also increases, generating economies of scale as the fixed costs of collective management of the ditch system diminish as a percentage of the overall farm revenues. Larger systems are also more able to take out debt for infrastructure projects, since land is often used as collateral in agricultural contexts. Finally, larger systems are more politically powerful in the SLV because they make up such a high percentage of overall agricultural production, and this political power can be used to access resources from the federal and state governments. The acequia variable also provides some socio-economic information as well, since those systems tend to have smaller farms, lower yields per acre, and less political power. System size and acequia status also correlate with the number of irrigators, an important variable for which data is also unavailable.

2.5.2. Analytical Methods

To analyze the data, I employ regression methods using two-tailed significance tests. Following Gujarati & Porter (2009), I evaluate several between-estimator regressions which average data over time for the entire time series. I also
run regressions on data averaged over quintile subsets by Snow Water Equivalent (SWE) (the middle quintile contains eight years of data, the others six). Tobit regressions were also run on data from the year 2002, the worst drought on record. Model diagnostics were performed. Heteroscedasticity and auto-correlation robust standard errors were reported for following Gujarati & Porter (2009) and Zeileis (2004) where appropriate. Models without interactions on the matched, time-averaged data and the matched, time-averaged data subset by SWE took the form:

\[ y_i = \beta_0 + \beta_1 PRIORRANK_i + \beta_2 UPRANK_i + \beta_3 TRIB_i + \beta_4 ACEQUIA_i + \beta_5 CATCHAREA_i \\
+ \beta_6 AREA_i + \beta_7 ELEV_i + \beta_8 SWE_i + \beta_9 RES_i + \beta_{10} PERMULIT_i + \beta_{11} GROUND_i \\
+ \beta_{12} SPRINK_i + \beta_{13} WD_i + \epsilon_i \]

When regressing the dependent variables percent maximum diversion and months of active diversion, the independent variables groundwater access, sprinkler use, and percent area irrigated by multiple ditch systems were excluded, since these would not impact those outcomes. Models with interactions and for the year 2002 are of essentially the same form and use data from 2002 only where appropriate. See Section A3.2 and A3.3 of Appendix A for more information on the models.

2.6. Results

Results from regressions on data averaged over the study period are presented in Table 2.4. In agreement with the first hypothesis, results show that
higher ranked water rights are consistently and significantly associated with better irrigation performance.

Table 2.4. Between estimator regression outputs for the three dependent variables.

<table>
<thead>
<tr>
<th>Regression Output from Matched Data Averaged over 1984-2015</th>
<th>Percent Area Irrigated (1)</th>
<th>Percent Maximum Volume Diverted (2)</th>
<th>Months of Active Diversion (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.1828***</td>
<td>0.3621***</td>
<td>0.5223***</td>
</tr>
<tr>
<td></td>
<td>(0.0449)</td>
<td>(0.0381)</td>
<td>(0.0420)</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>-0.1230*</td>
<td>-0.1485**</td>
<td>-0.0933</td>
</tr>
<tr>
<td></td>
<td>(0.0688)</td>
<td>(0.0590)</td>
<td>(0.0784)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.4352***</td>
<td>-0.2576**</td>
<td>-0.0616</td>
</tr>
<tr>
<td></td>
<td>(0.1304)</td>
<td>(0.1135)</td>
<td>(0.1210)</td>
</tr>
<tr>
<td>Acequia</td>
<td>-0.0439</td>
<td>-0.0513</td>
<td>-0.1461</td>
</tr>
<tr>
<td></td>
<td>(0.1440)</td>
<td>(0.1221)</td>
<td>(0.1219)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.1768**</td>
<td>0.4785***</td>
<td>0.4261***</td>
</tr>
<tr>
<td></td>
<td>(0.0874)</td>
<td>(0.0570)</td>
<td>(0.0578)</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.0014</td>
<td>0.0809**</td>
<td>0.1323***</td>
</tr>
<tr>
<td></td>
<td>(0.0414)</td>
<td>(0.0388)</td>
<td>(0.0451)</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.0175</td>
<td>0.0296</td>
<td>0.0189</td>
</tr>
<tr>
<td></td>
<td>(0.0559)</td>
<td>(0.0512)</td>
<td>(0.0567)</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>0.1122**</td>
<td>0.0947**</td>
<td>0.1527***</td>
</tr>
<tr>
<td></td>
<td>(0.0522)</td>
<td>(0.0467)</td>
<td>(0.0492)</td>
</tr>
<tr>
<td>Percent Years Accessing Reservoir</td>
<td>0.0862*</td>
<td>0.1396***</td>
<td>0.1884***</td>
</tr>
<tr>
<td></td>
<td>(0.0517)</td>
<td>(0.0424)</td>
<td>(0.0411)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td>-0.0653</td>
<td></td>
<td>(0.0456)</td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.0621</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1215)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler</td>
<td>-0.2940</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.2184)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td>400</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>R²</td>
<td>0.3629</td>
<td>0.5174</td>
<td>0.4832</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.3311</td>
<td>0.4974</td>
<td>0.4617</td>
</tr>
<tr>
<td>Residual Std. Error</td>
<td>0.8179 (df = 380)</td>
<td>0.7090 (df = 385)</td>
<td>0.7337 (df = 385)</td>
</tr>
</tbody>
</table>

Note: Water District and constant omitted from the table but included in the regression. Heteroscedasticity and autocorrelation robust standard errors reported where appropriate. *p<0.10; **p<0.05; ***p<0.01
In agreement with the second hypothesis, a larger catchment area is also consistently significantly associated with better irrigation performance. The third and fourth hypotheses – that diverting from a tributary and diverting below many irrigators are harmful, respectively – are essentially supported, though less strongly than the first two hypotheses. Finally, in agreement with the fifth hypothesis, several other variables significantly interact with water right priority to mediate priority’s effect on irrigation performance.

2.6.1. Hypothesis 1: Water Rights Are Highly Influential

As shown by Table 2.4, in all regressions performed on matched and standardized data averaged over the entire time series, increasing seniority of water right improves all measured irrigation outcomes with significance to \( p < 0.01 \). Water right priority rank is especially beneficial for months of active diversion, which would be expected given the nature of PA. Moving up a standard deviation on water right priority rank improves months of active diversion by 0.52 standard deviations. The weakest signal of water rights is on the average percent acres irrigated, which increases only 0.18 standard deviations for every standard deviation increase in water right priority rank. The coefficients on water right priority rank and catchment area are not significantly different to \( p < 0.05 \) in any of the three regressions in Table 2.4.
2.6.2. Hypothesis 2, 3 and 4: Diversion Location Matters for Performance

2.6.2.1. H2: Catchment Area

Table 2.4 demonstrates that increasing catchment area improves all measured irrigation outcomes with significance to p < 0.05. Moving up a standard deviation catchment area improves months of active diversion by 0.47 standard deviations. The weakest signal of catchment area is on the average percent acres irrigated, which increases only 0.18 standard deviations for every standard deviation increase in catchment area.

2.6.2.2. H3. Tributary Diversion

As shown in Table 2.4, diverting from a tributary significantly harms (p < 0.01) the percentage of maximum irrigated acreage by 0.44 standard deviations. There is a smaller but still significant effect on percent of maximum volume diverted (-0.26, p < 0.05), and no significant effect on the months of active diversion.

2.6.2.3. H4. Upstream Rank

Table 2.4 demonstrates that upstream rank is the least supported hypothesis of the first four evaluated. Only for percent maximum volume diverted is the coefficient significant (p < 0.05). However, it is in the expected direction, albeit with relatively smaller magnitude (-0.15) than the other variables evaluated.

2.6.3. Hypothesis 5: Influence of Water Rights Depends on Other Variables

In addition to the results on H1-H4, interactions were performed between water right rank and other relevant variables and regressions were performed on
subsets of data (see Sections A4 and A5, Figures A.6-A.20, and Table A.3 and Table A.4 in Appendix A). These analyses reveal that the effect of water rights depends on contextual factors.

2.6.3.1. H5: Snowpack

Of particular interest in an era of climate change is the influence of snowpack on the impact of water right priority rank. Tobit regressions run on data from the year 2002 (Table A.5 in Appendix A) shows a similar pattern of results as those in Table 2.4. Because the coefficients are not comparable to those in Table 2.4, the significance levels should be evaluated to compare differences. In 2002, water rights, catchment area, and surface reservoir access are all strongly significant determinants of irrigation performance ($p < 0.01$). Upstream ranking and tributary diversion are not significant even to $p < 0.10$.

When data are subset by SWE (Tables A.6-A.8 in Appendix A), a similar pattern to the results shown in Table 2.4 are apparent. More useful, however, are comparisons between different SWE subsets. For percent acres irrigated, the coefficient on water right priority ranking is significantly higher ($p < 0.05$) for very dry and dry years when compared to wet years (but not very wet years). For percent maximum volume diverted, the coefficient on water right priority ranking is significantly higher ($p < 0.05$) for very dry years when compared to very wet and wet years and dry years when compared to wet years. There is no significant difference in the influence of water right priority ranking across subsets of years by climate for months of active diversion.
Finally, as Figure 2.3 demonstrates, water rights are also moderated by SWE on average. A similarly shaped, almost uniformly significantly positive curve exists for the other dependent variables (Figure A.13 and Figure A.18 in Appendix A).

**Figure 2.3.** Marginal effect plot of the interaction between water right ranking and SWE for percent acres irrigated. The gray area represents bootstrapped 95% confidence intervals, and the histogram on the x-axis shows the distribution of SWE across the units of observation.
2.6.3.2. H5: Catchment Area

The marginal effect of water right priority rank over different values of catchment area is significantly positive but declining as catchment area increases for all dependent variables (Figures A.6, A.11 and A.16 in Appendix A). For percent area irrigated, the effect drops to be statistically indistinguishable from zero for catchment areas larger than a standard deviation above the mean catchment area. This same result of statistically zero marginal effect of water right priority rank is obtained only on the largest catchments for percent maximum volume diverted. For months of active diversion, the marginal effect of priority ranking is positive but declining over the range of values of catchment area.

2.6.3.3. H5: Tributary Diversion

Interactions between water right priority rank and tributary diversion reveal significant differences between the influence of water right priority rank between systems diverting from a tributary and those diverting from a mainstem. Water right priority rank is significantly less influential (p < 0.01) on months of active diversion (-0.27) and volume diverted (-0.26) when diverting from a tributary. A similar but less significant (p < 0.10) and less strong effect (-0.15) is seen for percent acres irrigated. These results are presented in Figures A.10, A.15, and A.20 and Table A.4 in Appendix A.

2.6.3.4. H5: Upstream Rank

The marginal effect of water right priority rank over different values of upstream ranking is significantly positive but declining for all dependent variables
except percent maximum volume diverted (Figures A.7, A.12 and A.17 in Appendix A). For percent maximum volume diverted, an inverted U shape is observed that is always above zero marginal effect. For percent area irrigated, the effect drops to be statistically indistinguishable from zero for upstream ranks larger than a standard deviation above the mean upstream rank. This same result of statistically zero marginal effect of water right priority rank is obtained only on the most downstream systems for months of active diversion.

2.6.3.5. H5: Cultural Heritage

Interactions between water right priority rank and acequia status reveal no significant difference between the influence of water right priority rank between acequias and non-acequias. These results are presented in Figures A.9, A.14, and A.19 and Table A.3 in Appendix A.

2.6.3.6. H5: Higher Level Policy

The interaction between water right priority rank and a dummy variable indicating whether a diversion is located on a stream subject to the RGC is not significant. The marginal effect of water right priority rank does not differ between ditches subject to the RGC and those not subject to the RGC. When water right priority rank is interacted with a categorical variable with three possible values – Closed Basin, Rio Grande Compact, and Non-Tributary – the marginal effect of water right priority rank is not significantly different between any of these categories. Only WD26, Saguache Creek, shows a significantly higher (p < 0.05)
influence of water right ranking when compared to other WDs. This result exists for all dependent variables.

2.7. Discussion

2.7.1. Hypothesis 1: Water Right Priority Rank

Increasing water right priority rank is significantly associated with agriculturally meaningful improvements in irrigation performance. The consistently positive significant influence of increasing water right priority rank almost certainly because water rights are monitored and enforced between irrigators themselves and by the state (Castex, et al., 2015; Goldstein & Hudak; 2017; Hurlbert & Mussetta, 2016; Torpey-Saboe, et al., 2015). Contemporary literature in Western US suggests water rights matter (Xu et al., 2014a; Xu et al., 2014b). Some of the literature on water in the Western United States has been skeptical of the real world application and influence of PA due to various higher level policies (Benson, 1998, 2012; Tarlock, 2000, 2001). However, in this case, the RGC does not appear to change the influence of water right priority on average.

It is possible but unlikely that the strong and reliable influence of water right priority is being misconstrued. This is because priority ranking is essentially a question of who got to the SLV first. Farmers on ditches with senior water rights may have a generation or two advantage in local knowledge and capital accumulation and therefore could simply be more effective farmers. However, farming methods have changed dramatically since the 1850s, and due to turnover
on ditch systems, new farmers may not absorb or inherit the local knowledge and capital of previous generations of farmers. It could also be argued that founders of the first ditch systems simply picked the best land. However, the best land would be more likely to increase crop production than duration of active diversion, amount of water diverted, and percentage of acres irrigated. In this analysis, water right priority has the strongest influence on variables related directly to water (months of active diversion, percent maximum volume diverted), as opposed to crops (percent acres irrigated). Thus, it is more likely that the signal is related to water right priority itself and not the quality of the land for farming or the quality of the farmers. Overall, this analysis adds to the growing body of evidence that property rights are influential when they are enforced (Meinzen-Dick, 2014; Torpey-Saboe, et al., 2015; Xu et al., 2014a, 2014b) and that higher levels of policy can matter for the real-world implementation of property rights (Ostrom, 2005).

2.7.2. Hypothesis 2: Catchment Area

As expected (Lam, 1998; USDA, 2012b), increasing catchment area improves irrigation performance. Systems with the largest catchment areas are more likely to have physical access to larger volumes of water throughout the year. As illustrated by the regressions on data subset by SWE, because larger catchments have larger flow volumes, this positive effect becomes even more important during drought when flow volumes are limited. During dry and very dry years, for percent
maximum volume diverted, catchment area is significantly (p < 0.05) more influential than water right priority rank (Table A.7 in Appendix A).

It is unlikely this result is being misconstrued. Larger catchment areas should be found on systems farther downstream with more diversions upstream of them, yet the influence of catchment area is positive while the influence of upstream ranking is negative. That these influences are in opposite directions and that these influences are in their expected directions gives credibility to the straightforward interpretation advanced here. And while tributaries are likely to have smaller catchment areas and thus confound these results, by including tributary diversion and elevation in the regressions, it is unlikely that the results are being biased.

2.7.3. Hypothesis 3: Tributary Diversion

Although this result is not statistically significant for months of active diversion, the result is as expected (Lam 1998; Xu et al., 2014b): diverting from a tributary harms irrigation performance, particularly irrigated acreage. With fewer streams feeding a diversion on a tributary, there are fewer independent sources of supply to rely on, increasing the variability of water supply. This effect is strongest for percent acres irrigated and during drought (Table A.6 in Appendix A). This implies that without a diversity of catchments in shortage, each melting off snow at different times and rates, irrigation systems cannot on average divert enough water to reliably irrigate their land despite diverting water for an equivalent number of
months as those on mainstems. It may be that irrigators, as individuals, understand that the runoff from a given catchment is somewhat unpredictable, as the hydrograph depends on seasonal factors such as snow depth and density, dust accumulation on the snow, wind direction and speed, tree cover, cloud cover, local temperature variations, and soil saturation, among other influences. Not wanting to lose a crop, this high variability prompts them to plant acreage conservatively, and results in lower irrigated acreage individually – and when summed, collectively – on tributaries. It is also true that in the SLV irrigation systems on tributaries are more likely to be used by ranchers growing native meadow hay, and therefore these systems have higher variability in irrigated area due to crop choice, leading to lower than average percent area irrigated during droughts.

2.7.4. Hypothesis 4: Upstream Rank

The fourth hypothesis is not strongly supported. Only for percent maximum volume diverted is the coefficient significant (p < 0.05) and the effect size is relatively small, though it is in the expected direction (-0.15). Without any of the other factors in place, this would be surprising (Janssen et al., 2011; Lam 1998), especially considering the local aphorism that it is “better to be upstream with a shovel than downstream with a water right.” However, because of the strong influence of water rights, geographic features like catchment area and tributary diversion, and surface reservoirs in drought, the lack of strong support for this hypothesis is perhaps unsurprising. It appears that, overall, water rights are more
influential in the SLV than the number of users upstream. That said, overall, it is better to be upstream than downstream, given that in all regressions performed – including on data subset by climatic conditions – the coefficient on upstream ranking is negative and significant for percent maximum volume diverted, an important outcome for irrigation systems.

2.7.5. Hypothesis 5: Water Rights in Context

2.7.5.1. H5: Weather and Climate

Figure 2.3 illustrates that the marginal effect of water right priority rank has an inverted U shaped curve, where water rights have lower or no influence on average for systems that experience high and low levels of snowpack. Consider that for senior right holders, water right priority rank does not explain much of the variation in the outcome variables, because seniors are essentially not restricted in their ability to access water except in very dry years. Therefore, junior irrigators deserve more attention. One explanation for this inverted U shaped curve is that when there is ample water available as snowmelt, the restrictive nature of PA does not take effect – fewer junior irrigators are curtailed because more seniors are satisfied, and therefore water rights have less influence. At very low levels of snowpack, the physical rather than legal availability of water is a limiting factor and even some seniors are cut short. Only at moderate levels of snowpack, when sufficient snow is available for most users to get at least some water, does the lifting of the limits imposed by PA on junior irrigators make a difference for outcomes.
2.7.5.2. H5: Cultural Norms

The results do not support the hypothesis that cultural norms have a moderating effect on the influence of water right priority rank on the outcomes measured. These results undermine Kamran & Shivakoti (2013), who found that a water management regime which did not conflict with local norms and evolved in the community rather than being imposed by a colonial power was more stable. That said, in support of Kamran & Shivakoti (2013), one explanation for the strong influence of PA overall is that it was codified based on local norms of Anglo irrigators in the late 1800s. Absolute respect for private property rights is an important cultural factor in the United States, especially around water (Goldstein & Hudak; 2017). It is possible that there are in fact moderating effects of being an acequia that this study is not equipped to detect. The measure of acequia status does not take into account the present-day ditch-level rules, but instead assumes a more culturally engrained set of norms that may have faded to the point that this study cannot detect them. Furthermore, the outcome measures used here would be best equipped to detect whether the repartimiento was still in place, the norm most in conflict with PA. Based on conversations with irrigators, there has been a coevolution of the historical common property regime of Hispanic irrigators and the private property regime imposed by PA on systems what were undoubtedly founded as acequias (Tang & Gavin, 2015). This coevolution has likely resulted in a muting of the influence of traditional acequia norms, especially the repartimiento.
2.7.5.3. \textit{H5: Geography}

For percent maximum volume diverted, there are clear signs that at the extremes of catchment area and upstream ranking these variables become more powerful influences on outcomes and reduce the influence of water right priority rank (Figures A.11 and A.12 in Appendix A). Percent area irrigated and percent maximum diversion, being far downstream and having a very large catchment area reduce the influence of water right priority rank to zero. The logic for this is the same as the logic used to explain the inverted U shaped curve observed for marginal effect of water right priority when moderated by SWE: an irrigation system that is limited or enabled by some other factor will be less influenced by water right priority rank than would otherwise be the case. As for tributaries, it is clear that, similar to SWE, when water supplies are strongly physically limiting, as they more frequently are on tributaries, water right priority rank has lower levels of influence.

2.7.5.4. \textit{H5: Higher Level Policy}

Despite the lack of evidence for the influence of higher level policy such as the RGC arising from interactions, it is possible that the RGC’s influence is more subtle. Interestingly, WD26 – Saguache Creek – shows a significantly (p < 0.05) stronger influence of water right priority than other WDs for all outcomes. This may be due to numerous factors, but four stand out. First, WD26 is not administered for the Rio Grande Compact, and so no rights holders are curtailed to satisfy deliver requirements, leaving their influence unmuted. Second, interactions between water right priority and tributary diversion show that on tributaries, water rights are less
influential, and WD26 has fewer tributary diversions than most other WDs, increasing the influence of water right priority in WD26. Third, WD26 does not have any surface reservoirs, which are significantly associated with irrigation performance; a lack of surface storage would logically be expected then to increase the importance of other factors, including water right priority. Finally, WD26 has no acequias, and while this did not show up as a significant factor in determining the influence of PA, it is still plausible that a lack of acequias increases the importance of water right priority within a watershed. Combined, these factors could help explain why WD26 shows a more significant influence of water right priority rank than other WDs. There could be other unobserved factors at play (such as more stringent monitoring), but the conclusion is straightforward: water right priority matters most in this district, and this district is the most comparable district without RGC administration to the districts under RGC administration.

### 2.8. Chapter Conclusion

So, is it better to be upstream with a shovel or downstream with a water right? It appears it is better to be downstream with a senior water right, to a point. An irrigation system would have to be very far upstream to overcome the negative influence of being even a moderately junior irrigator. In the SLV at least, water right priority rank is the more consistently and more strongly beneficial than any other variable evaluated with the exception of catchment area, which has a comparable influence. And water rights have more say than geographic factors such
as upstream rank and tributary diversion, despite their influence being significantly moderated by geography and climate. However, in extreme drought, access to a surface reservoir is in the same range of importance as water right priority ranking (Table A.5 in Appendix A). There are several policy implications of this research. The findings have implications for the effects of property rights in natural resources and add to the value of understanding institutions in context for irrigation in an era of climate change (Castex, et al., 2015; Hurlbert & Mussetta, 2016), especially given that the influence of water right priority rank was highly sensitive to climatic conditions. Policy makers can use this research to better understand the interaction between water rights, geography, higher level institutions, and cultural norms. Indeed, the different influence of different factors on different outcomes illustrates the importance of careful, locally specific management strategies, even within the same river basin (Alcon, et al., 2014). Additionally, the variable influence of water rights in this study depending on context should lend credence to the idea that enforced water rights are not a panacea that will improve all outcomes in all contexts (Meinzen-Dick, 2007). It is likely that these findings are generalizable to snowmelt driven irrigation systems where water rights are strongly enforced (Torpey-Saboe, et al., 2015; Xu et al., 2014a, 2014b), given the diverse array of irrigation systems sampled and the ability to test inferences using the separate WDs within the SLV.

A key point is that these findings apply to de facto water rights, and that in this study de facto water rights and de jure water rights are the same. More work
should be done to assess the relative importance of *de facto* and *de jure* water rights in situations where they differ, and how proportional rights regimes may differ from priority systems or permit-based, market-oriented approaches. PA may have different outcomes compared to proportional systems that are less sensitive to the amount of water available, such as the *repartimiento* historically practiced by *acequias*. Chapter 4 addresses this to some degree. Further questions also persist regarding climate change. More work needs to be done to assess how water rights perform under prolonged drought and what other tools, such as user-driven institutional change, might be needed to ensure resilience under persistently increasing aridity. This alludes to another limitation of this chapter, which is that it did not consider heterogeneities in performance within the same irrigation system. Beyond water rights, irrigators using the same irrigation system can make rules that alter outcomes between them. How these rules influence performance at different levels of water scarcity is the focus of the next chapter, Chapter 3.
CHAPTER 3

FLEXIBLE WATER RIGHTS AND ROTATIONAL DELIVERY COMBINED
ADAPT IRRIGATION SYSTEMS TO DROUGHT

3.1. Climate Change and Self-Governing Irrigation Systems

Improving global food security will be made more challenging by a changing climate (Bell et al., 2013; Turrall et al., 2011; Wheeler and von Braun, 2013). Because climate change will alter water supplies, irrigated agriculture in particular will suffer (FAO, 2012; Gleick, 2003). This is especially true for irrigators who rely on snowmelt (Vicuña et al., 2012; Villamayor-Tomas, 2012). This is problematic because irrigation is expected to be responsible for meeting growing demands for food and already accounts for 40 percent of the world’s food supply (UNESCO, 2012). Worldwide, about three quarters of irrigated cropland and one quarter of all cropland relies on self-governed irrigation systems (Mabry, 1996), while fully 90 percent of all irrigation systems are small-scale and self-governed (Cifdaloz et al., 2010). An irrigation system – the diversion dam, diversion structure, canals, weirs, sluices, and other infrastructure – is self-governed when farmers with rights to access the water conveyed by the system own, operate, maintain, and manage the system. Thus, irrigators themselves will be tasked with the vast majority of
adaptation, yet scholars, policy-makers, and irrigators themselves may not know enough to be adequately prepared for climate change (Kramer et al., 2017).

Farmers in the US state of Colorado are a good test case for questions related to climate change adaptation in irrigated agriculture. Just over half of the farmland in Colorado is irrigated by self-governing irrigation systems (Sax et al., 2006; USDA, 2012a), and about four fifths of stream flow start as snow (CCC, n.d.). Although potentially offset by CO2 fertilization and an extended growing season (Deryng et al., 2016; Wiltshire et al., 2013), farmers nevertheless face mounting climate change challenges: more severe forest fires and forest composition changes (Lukas et al., 2014), declines in snowpack volume and earlier spring melt (Koirala et al., 2014; USBOR, 2013), and increased crop water demand due to rising temperatures (Lukas et al., 2014). The SLV, where a community of 50,000 irrigates between 140,000 and 200,000 hectares, may be the most negatively impacted in Colorado and has already seen climatic changes (Lukas et al., 2014; Mix et al., 2009, 2011, 2012). Early signals of climate change have already prompted responses from irrigators, especially those dependent on groundwater (Cody et al., 2015; Smith et al., 2017).

Many scholars, policy makers, and irrigators see improvements to irrigation systems as important to adaptation (FAO, 2012; Lee et al., 2014). Some of the improvements envisioned are institutional changes; that is, changes to laws, policies, rules, and norms (Huntjens et al., 201; Kenney, 2005; Meinzen-Dick, 2014; Ostrom, 2005). Particular attention has been paid to property rights to water (Cody,
However, property rights can be very difficult to change, and government-imposed rule changes are often resisted (Poteete et al., 2010). To compensate, irrigators on self-governing systems have developed local adaptations to shortage which manipulate two of the major influences on water use they control: rules governing water allocation and water distribution among members (Dinar et al., 1997; Joshi et al., 1998). This study investigates the effectiveness of two common drought responses of irrigation systems, water delivery via rotation and shortage sharing, in four configurations: rotation with shortage sharing, rotation without shortage sharing, simultaneous delivery with shortage sharing, and simultaneous delivery without shortage sharing. Effectiveness is evaluated at different levels of water shortage and for water users at different points along the irrigation system’s water conveyance network. Rotation in this paper is defined as water delivery which occurs in turns, regardless of the duration of the turns or the sequence of delivery. Shortage sharing is defined in this paper as the alteration water allocations between users of the same irrigation system in times of drought, regardless of the original criteria used to allocate water (land owned, private rights held, historical use, etc.).

The CPR literature has begun to emphasize the configurational nature of rules (Baggio et al., 2016), but there is still much to learn about how different configurations influence the outcomes of CPR governance, such as equity (Ingram et al., 2008). Fairness and equality are of utmost importance: many studies have shown that perceptions of fairness in a self-governing CPR context are important
for maintaining the collective action necessary to maintain the flow of resources to users (Arnold, 2008; Cody et al., 2015; McCord et al., 2017; Pérez et al., 2016; Poteete et al., 2010). In irrigation, a ubiquitous issue is the potentially highly unequal relationship between irrigators upstream (head-enders), who have the ability to withdraw water first and in the largest amounts, and downstream (tail-enders), who must wait for water to flow past head-enders and can only take what is left (Janssen et al., 2011, 2012). Additionally, different levels of water shortage should generate different irrigation outcomes even with the same rules in place, as Cody (2018b) found with respect to water rights. Therefore, in this study, the effectiveness of the aforementioned configurations is evaluated at different levels of water shortage and for fields at different distances from the irrigation system’s main diversion.

To do this, a natural experiment in the use of rotation and shortage sharing during a period of drought (2011-2014) in the SLV is exploited. Drought creates the water shortage that triggers the implementation of the rotation and shortage sharing rules under study, and these rules serve as the different treatments. Hydrologic, technological, agronomic, and remotely sensed crop data (NDVI) were paired with data on over 6,700 individual fields nested within 60 self-governing irrigation systems for the years 2011-2014. The data are complemented by a stratified irrigation manager survey conducted in 2013 which assessed the rules in use of those systems, among other features. The study area and sampled irrigation systems are depicted in Figure 3.1. Because variables of interest are time invariant,
the data were analysed one year at a time using Ordinary Least Squares (OLS) linear regression and logistic regression with standard errors clustered by irrigation system. Tobit regression and spatial error and spatial lag models were performed as robustness checks.

**Figure 3.1.** Map of the SLV (data from CDWR, n.d.).

![Map of the SLV](image)

The results show that not only are these configurations significant predictors of irrigation performance, there is also a significant interaction between the configurations and context. The rule configurations have significantly different impacts on the degree to which head-end fields and tail-end fields have divergent levels of crop production, and these effects are further moderated by the amount of...
water available. In particular, rotational delivery with shortage sharing, the most frequent combination of rules in the sample, has the capacity to equalize NDVI between head-enders and tail-enders across all levels of water shortage. It also produces nearly equal marginal productivity of water, i.e. increases in crop growth per additional unit of water, between head-enders and tail-enders across all levels of water shortage. Rotation with shortage sharing consistently performs well compared to other configurations with less equal outcomes, even if in some water shortage conditions other configurations out-perform it. Because of its more equal outcomes, and because it competes well with other configurations in drought, it is likely that rotational delivery with shortage sharing best promotes the collective action necessary to adapt self-governing irrigation systems to a more arid and unpredictable future in the SLV and elsewhere. That said, the precise forms of rotation and shortage sharing cannot be prescribed from this analysis. Indeed, in some cases, only rotation, only shortage sharing, or neither rule may be warranted. Further investigation of individual irrigation systems would be necessary to determine the exact rules which would optimize performance under a diverse set of conditions (Cifdaloz et al., 2010; Pérez et al., 2016). Nevertheless, this study gives irrigators more certainty about the outcomes of the options they have.

### 3.2. Rotation and Shortage Sharing: Influences and Interactions

Two universal institutional features of self-governing irrigation systems are water allocation rules and water distribution rules (Dinar et al., 1997; Joshi et al.,...
They are especially worthy of study due to their direct and fundamental influence on water use, and therefore water demand and ecological impacts. In the context of irrigation, water allocation rules pertain to how much water each farmer within an irrigation system can use (e.g. 9,200 cubic meters per hectare of land owned), and distribution rules determine how that water reaches the farmer (e.g. for sequential 12-hour turns) (Dinar et al., 1997; Joshi et al., 1998; Ostrom, 1992). One of each of these types of rules is the focus of this study, because they are known adaptations to shortage (Abdullaev et al., 2006; He et al., 2012) and are therefore likely to be important for adaptation to climate change. They determine, (1) whether or not water allocations can be changed between individual irrigators on the same irrigation system (i.e. “shortage sharing”; de facto temporary transfers of the usufruct water right), and (2) whether the flow of the ditch is delivered to individual irrigators in a rotation or divided among them simultaneously. Irrigation systems in the SLV under normal water availability may or may not rotate, with some switching to rotation and some changing the rotation itself during shortage. However, while there are myriad manifestations of these rules in practice (e.g. multiple forms of rotation, multiple criteria for determining water allocations), some level of abstraction is required to make general inferences about their influence, and so they are considered binary in this study.

Delivery and allocation rules interact with key human and hydrologic behaviors, specifically the incentive to over-use or steal water and the fact that water is lost to seepage and some evapotranspiration down the length of an earthen
canal. Irrigation managers in the SLV reported anywhere from 5-15% losses depending on the distance a farmer’s headgate is from the diversion structure, the slope of the ditch, soils, and ditch lining (e.g. concrete, bentonite, nothing), vegetation along the ditch, height of the water table, etc. This implies that seepage loss can become a major factor for irrigators to consider during shortage. Most irrigation managers also reported some level of water theft, usually more damaging during shortage and on larger systems where monitoring is difficult.

Important for this study, water rights in the SLV are administered by the state of Colorado at the point where water is diverted from the natural water source through a human-made diversion structure and into the human-made irrigation network. Beyond the diversion structure, the state does not directly interfere with how water is allocated on the irrigation system. The allocation and distribution rules being investigated were adopted by irrigators themselves based on the coevolution of contextual factors, such as law and geography, and irrigator preferences (Ostrom, 2014). The decision to implement institutional adaptations to shortage such as rotation or shortage sharing is generally based on snowpack or streamflow and determined by an informal dialogue between irrigators, though it may be taken to a vote. Irrigators on the same irrigation system usually interact almost daily during irrigation season, and nearly all systems have an annual meeting prior to the season to discuss the ongoing needs of the system, potential changes, and whether to implement adaptations to shortage. The process of rule adoption is historically contingent; irrigators in this region have been continuously
operating their systems as far back as the 1850s and pass land down largely from fathers to sons. Therefore, in a highly path dependent process (North, 1990), these distribution and allocation rules have evolved slowly over time to accommodate new users, new technologies, changes in water law, changes in the hydrologic context, and other influences. Depending on the collective choice rules of the irrigation systems, operational rules of allocation and delivery are selected through majority vote, consensus, inherited tradition, hegemonic behavior of a few powerful irrigators, or some other decision process. Whatever the case, each configuration is ultimately the product of coevolving contextual factors and irrigator preferences (Ostrom, 2014). Irrigators report that changes to their rules have produced meaningful changes in crop production in the past, and among irrigators the importance of allocation and distribution rules is widely acknowledged.

Looking first at delivery rules, under rotation, users can easily monitor each other at the main canal as they take turns diverting water. Monitoring in the SLV is conducted almost exclusively by eye – there are very few irrigation systems where electronic ditch gates and gages are in use. Under rotation, the next farmer in turn will be at the ditch, engaged in \textit{de facto} monitoring, sometimes in the middle of the night. Although requiring increased negotiation, management, and operational costs, rotation thus helps prevent “stationary bandit” behavior (Janssen et al., 2011, 2012), wherein head-enders take advantage of being first in line to extract water and deprive tail-enders of their full allocation (Lam, 1998; Ostrom, 1992). If left unchecked, stationary bandits eventually cause tail-enders to become
helpless to match the elevated extraction of head-enders, and in the extreme tail-enders get no water at all. In contrast, rotation creates an affirmative requirement to deliver water to all users, potentially improving collective action through time (Dayton-Johnson, 2000; Pérez et al., 2016).

Because rotation generally allows the full flow of the ditch to reach each irrigator, it has four importantly different hydrologic impacts compared to simultaneous delivery (described in the next paragraph): 1) rotation generates enough hydraulic head to “push” sufficient water the full length of the ditch (Lam, 1998); 2) rotational “pulses” more quickly saturate the root zone over a given area of land as compared to continuous application of the same volume; 3) depending on the rate of flow, rotation can overwhelm individual irrigators’ infrastructure, crops, and/or soils, wasting water or even lowering crop growth by water logging or eroding soils or damaging water control infrastructure; and 4) depending on how turns are taken, rotation may cause water to flow over a dry ditch bed at the start of turns, increasing seepage losses compared to simultaneous delivery which keeps the ditch bed wet constantly.

On systems that distribute simultaneously, the flow is divided among users according to de facto rights between them at the same time. Three key features of simultaneous delivery include: 1) Greater transaction costs to establish monitoring and more difficulty in monitoring because of the need to monitor many water users at once, potentially leading to less monitoring; 2) No affirmative delivery requirement to tail-enders (or anyone, for that matter); and 3) Decreases water
supply reliability to tail-enders due to divided hydraulic head and thus worse seepage losses relative to rotation. Together, these features encourage theft and hegemony by head-enders as well as potentially more severe seepage losses. However, they may also ensure predictability of flow for most users most of the time. Simultaneous delivery is also inexpensive to organize and administer in terms of time and labor. Finally, the lack of turn-taking simplifies transfers, infrastructure needs, and maintains a consistently saturated ditch bed over the distance that water flows, eliminating the need to repeatedly saturate the bed when rotating turns.

The other rule in use under consideration in this study, shortage sharing, implies flexibility in the ownership of de facto water rights. This flexibility should allow for more efficient allocations of water, enabling irrigators to improve the vigor of already planted crops, reliably plant more area, and earn revenue on unused water (He et al., 2012). Shortage sharing should improve marginal productivity in most cases by allocating water to lands with greater needs. Without the flexibility of shortage sharing, there is likely to be lower aggregate production than could otherwise be achieved. However, this flexibility can also increase the costs of monitoring water use by creating ambiguous water rights. Higher monitoring costs introduced by shortage sharing could lead to lower levels of monitoring, thus encouraging water theft and reduced irrigation performance, especially for tail-enders. However, if rotation is in place, this effect may be mitigated. Furthermore, shortage sharing will alter the hydraulic head, seepage losses, and return flows from
irrigation applications not fully consumed. This would harm tail-enders relative to head-enders and would be more damaging under simultaneous delivery because of the lack of an affirmative delivery requirement.

### 3.3. Hypotheses and Predictions

From the above, it is clear that the consequences of one rule depend on the adoption of the other rule, leading to H1: the effect of shortage sharing on irrigation performance depends on how water is being delivered, and the effect of the delivery method on irrigation performance depends on whether shortage sharing is practiced. Using rotation, with higher monitoring and higher hydraulic head, shortage sharing will be helpful due to increased flexibility, allowing water to flow to fields most in need. Under simultaneous delivery, with lower monitoring and lower hydraulic head, shortage sharing will be harmful due to stationary bandit behavior and seepage losses. Without shortage sharing’s increased flexibility, rotation may be harmful due the rate of flow being variable and thus water may be insufficient for or overwhelm infrastructure, soils, or crop demand. Finally, without shortage sharing, simultaneous delivery will tend to produce stationary bandit behavior and, in severe shortage, difficulty generating enough hydraulic head to move water the full length of the irrigation system.

What is also clear is that the effects of the rules in use will depend on water availability and how far water has had to flow from the diversion structure to the field, leading to H2: the effects of shortage sharing and delivery rules on irrigation
performance are moderated by the amount of water diverted by the irrigation system and a field’s distance from the diversion. Rotational delivery should equalize irrigation performance between head-enders and tail-enders regardless of water availability and shortage sharing rules, but without shortage sharing could prove inflexible to changes in water availability, leading to worse performance as higher levels of water availability overwhelm the system. Shortage sharing should harm tail-enders under simultaneous delivery, especially in extreme drought. But with rotation, shortage sharing should stabilize irrigation performance at higher levels of water availability through more efficient transfers. Rotation with shortage sharing, however, should harm performance at low levels of water availability due to the hydrologic inefficiencies of turn taking and the agronomic problems associated with very few pulses of irrigation water. Under simultaneous delivery without shortage sharing, there should be high inequality between the head and tail-ends and marginal productivity of crop per unit of water should be higher for head-enders who will capture the water ahead of tail-enders.

3.4. Methods

Careful case selection for natural experiments is increasingly encouraged when research questions cannot be answered using a laboratory, field experiments, or modeling; when study systems involve many different biophysical and social data; and when data are difficult or impossible to acquire or aggregate (Cox, 2015; Poteete et al., 2010). Natural-experiments such as this study require data about
numerous potentially confounding variables, and these data are seldom available at the same unit of analysis or resolution. However, the SLV overcomes many of these challenges due to the richness of its public data, the stability of the units of analysis, and six years of site visits by the author to ground truth the data and analysis. A period of drought in the SLV from 2011-2014 enables an evaluation of the rules in use during shortage, which serve as the different treatments in the study design.

3.4.1. Data Collection and Variable Development

Variables were drawn from CPR Theory and organized using the IAD framework (Ostrom, 2005). Variables were also selected in part due to their use to previous studies of irrigation in this region (Cox, 2010, 2014; Smith, 2014, 2016). The overall approach to the study is depicted in Figure 3.2. Water flows from left to right, being influenced by the variables in the diagram along the way. All the variables shown in Figure 3.2 are used in the regression analyses. The variables in italics are the independent variables of interest, while the rest are controls. The dependent variables are listed under Irrigation Performance. The variables selected are known to be important from the CPR literature and their relationships are structured using the IAD framework (Ostrom, 2005, Poteete et al., 2010). Contextual variables such as water availability and water diversion influence the decisions actors make in the action arena, considered here to be the user-governed ditch system. User decisions are shaped by features that apply to the irrigation
system as a whole, as well as features of individual irrigated fields. Outcomes of these processes include the decision to irrigate a field, how extensively, and the resulting crop growth.

**Figure 3.2.** A flow diagram containing the variables used in the analysis.

Data were collected from various public sources, primarily the Colorado Department of Natural Resources’ Rio Grande Decision Support Systems (RGDSS), the United States Geologic Survey, and GoogleEarth Engine (e.g. NDVI and elevation rasters). For the purposes of the regressions, irrigation system-level data were applied to the field observations in order to assess irrigation outcomes for individual fields. Figure 3.3 illustrates how NDVI raster data from GoogleEarth Engine, here July 2013, were overlaid by individual fields and irrigation system boundaries from RGDSS, here shown as vectors. When calculating the average
NDVI value for each field, the vector data were converted into raster data to compute zonal statistics in ArcGIS 10.5.

**Figure 3.3.** A map illustrating an NDVI raster overlaid by field and irrigation system vector data (data from CDWR, n.d. and GoogleEarth Engine).

Data were also collected using surveys of a stratified sample of 60 irrigation system leaders in 2013 to assess rules in use and other irrigation system features. Stratification was done by groundwater access (access/none), water right priority (senior/junior), geographic location (upstream/downstream), geographic location (four major watersheds), and cultural heritage (founded by the Spanish or by Anglo-Americans). The sample may therefore not be representative of the SLV overall, but
it will be better able to determine whether underlying effects exist that would
otherwise go undetected if the sample were not balanced on these key variables.

Surveys were administered in English and conducted in person at a location of the
interviewee’s choosing by two to three researchers at a time. One researcher led the
questioning and recording of responses, and the others took notes and confirmed
accuracy. To ensure that questions were asked and answers recorded consistently,
the groups of researchers were mixed each day.

Table 3.1. Variable descriptions, names, types, units, and summary statistics. A “f”
next to the shorthand name of the variable indicates a field-level variable. The rest
of the variables are collected at the level of the irrigation system. A “†” next to the
shorthand name of the variable indicates a time-variant variable. The rest of the
variables do not change over time.

<table>
<thead>
<tr>
<th>Variable Explanations</th>
<th>Shorthand Name</th>
<th>Variable Type; Units</th>
<th>Summary Statistics</th>
</tr>
</thead>
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<tr>
<td>Irrigation System Rotates Water Delivery in Scarcity</td>
<td>ROT_SRC</td>
<td>Binary</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Percent: 60.00</td>
</tr>
<tr>
<td>Irrigation System Engages in Shortage Sharing</td>
<td>SHR_SRC</td>
<td>Binary</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Percent: 65.00</td>
</tr>
<tr>
<td>Percent of Maximum Field Distance from Diversion</td>
<td>DIV_DIST f</td>
<td>Percentage</td>
<td>N: 6711</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min: 0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Med: 55.50</td>
</tr>
<tr>
<td></td>
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<td>Mean: 54.92</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SD: 22.06</td>
</tr>
<tr>
<td>Volume of Water Diverted Per Unit Area of Irrigation System</td>
<td>AFDIV_PERDACRE †</td>
<td>Continuous; 3083.7 cubic meters per hectare (acre-feet/acre)</td>
<td>N: 239</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min: 0.00</td>
</tr>
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<td></td>
<td>Med: 1.27</td>
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<td></td>
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<td></td>
<td>Mean: 2.06</td>
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<td></td>
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<td></td>
<td>Max: 13.41</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SD: 2.34</td>
</tr>
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<td>Field Irrigated or Fallowed</td>
<td>IRRFAL f†</td>
<td>Binary</td>
<td>N: 26844</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Percent: 57.71</td>
</tr>
<tr>
<td>Percent Field Area Irrigated</td>
<td>PMIA f†</td>
<td>Percentage</td>
<td>N: 26844</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min: 0.00</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Med: 70.99</td>
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<td></td>
<td></td>
<td></td>
<td>Mean: 50.92</td>
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<td></td>
<td></td>
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<td></td>
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<td>SD: 45.66</td>
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<tr>
<td>NDVI of Field</td>
<td>NDVI f†</td>
<td>Continuous</td>
<td>N: 26844</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min: 0.000</td>
</tr>
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| Name of Surface Water Source | WATER_SRC | Categorical | N: 60  
Rio Grande: 13  
Conejos River: 10  
Alamosa River: 7  
La Jara Creek: 6  
Culebra Creek: 5  
San Antonio River: 4  
San Francisco Creek: 3  
Rito Alto: 2  
Kerber Creek: 2  
Rito Seco: 1  
Costilla Creek: 1  
South Cuates: 1  
San Luis Creek: 1  
Sangre de Cristo Creek: 1  
Vallejos: 1  
Ventero Creek: 1  
Torcido: 1 |
|-----------------------------|-----------|-------------|----------------|
| Irrigation System Incorporated as Non-Profit Mutual Ditch Company | INC | Binary | N: 60  
Percent: 40.00 |
| Irrigation System Founded by Hispanics Between 1850-1880 | ACEQUIA | Binary | N: 60  
Percent: 53.33 |
| Quality of Irrigation System Infrastructure Deemed Problematic | INFRA | Binary | N: 60  
Percent: 40.00 |
| Access to a Surface Reservoir | RES | Binary | N: 60  
Percent: 41.67 |
| Percent Maximum Area of Irrigation System Irrigated on Average from 1984-2015 | PERMAXACIRRAVE | Percentage | N: 60  
Min: 2.63  
Med: 66.10  
Mean: 67.73  
Max: 116.81  
SD: 18.72 |
| Average Slope of Irrigation System | SLOPE | Continuous; Degrees | N: 60  
Min: 0.08  
Med: 0.46  
Mean: 0.67  
Max: 5.37  
SD: 0.79 |
| Water Right Priority Rank of Irrigation System | WDPRIOR | Continuous; Rank | N: 60  
Min: 1  
Med: 24.50  
Mean: 52.03 |
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<thead>
<tr>
<th>Category</th>
<th>Code</th>
<th>Type</th>
<th>Data</th>
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<tr>
<td>Irrigation System Owned by a Single Farmer</td>
<td>SOLEUSER</td>
<td>Binary</td>
<td>N: 60 Percent: 11.67</td>
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<tr>
<td>Irrigation System Appoints a Monitoring Agent</td>
<td>MONITOR</td>
<td>Binary</td>
<td>N: 60 Percent: 55.00</td>
</tr>
<tr>
<td>Irrigation System Allocates Water Based on Land Owned or Needs of the Farmer</td>
<td>LANDNEED</td>
<td>Binary</td>
<td>N: 60 Percent: 21.67</td>
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<tr>
<td>Quality of Irrigation System Soil Deemed Problematic</td>
<td>SOIL</td>
<td>Binary</td>
<td>N: 60 Percent: 23.33</td>
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<tr>
<td>Irrigation System Switches to Rotational Delivery in Scarcity</td>
<td>CNG2ROT</td>
<td>Binary</td>
<td>N: 60 Percent: 16.0</td>
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<tr>
<td>Field Distance to Nearest Stream</td>
<td>STRM_DIST</td>
<td>Continuous; Kilometeres</td>
<td>N: 6711 Min: 0.00 Med: 2018.60 Mean: 2734.20 Max: 11488.00 SD: 2488.75</td>
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<tr>
<td>Area of the Field</td>
<td>BASEACRES</td>
<td>Continuous; 0.4 hectares (acres)</td>
<td>N: 6711 Min: 0.06 Med: 24.81 Mean: 54.65 Max: 759.86 SD: 59.79</td>
</tr>
<tr>
<td>Field's Percentage of Total Irrigation System Area</td>
<td>ACREPER</td>
<td>Percentage</td>
<td>N: 6711 Min: 0.00407 Med: 0.150320 Mean: 0.894050 Max: 100.00 SD: 3.79</td>
</tr>
<tr>
<td>Total Area of the Irrigation System</td>
<td>DACRES</td>
<td>Continuous; 0.4 hectares (acres)</td>
<td>N: 60 Min: 29.24 Med: 1122.40 Mean: 8868.20 Max: 117320.00 SD: 20840.00</td>
</tr>
<tr>
<td>Field Irrigated by Multiple Diversions</td>
<td>MULTD</td>
<td>Binary</td>
<td>N: 6711 Percent: 19.74</td>
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<tr>
<td>Irrigation System Has South-Facing Aspect</td>
<td>SOUTH</td>
<td>Binary</td>
<td>N: 60 Percent: 20.00</td>
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<tr>
<td>Percent Average Annual Runoff at Upstream Gage</td>
<td>PERAVAFGAGE †</td>
<td>Percentage</td>
<td>N: 240 Min: 6.07 Med: 62.79 Mean: 61.25</td>
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<td>Nearest the Diversion Structure</td>
<td>Field Uses Sprinkler Irrigation</td>
<td>Max: 100.00 SD: 25.31</td>
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<tr>
<td>---------------------------------</td>
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<td></td>
</tr>
<tr>
<td>Field Uses Sprinkler Irrigation</td>
<td>SPRINK f†</td>
<td>Binary</td>
<td></td>
</tr>
<tr>
<td>Current or Most Recent Crop Grown on a Field</td>
<td>CROP f†</td>
<td>Categorical</td>
<td></td>
</tr>
<tr>
<td>Field Has Groundwater Access</td>
<td>GROUND f†</td>
<td>Binary</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nearest the Diversion Structure</th>
<th>Field Uses Sprinkler Irrigation</th>
<th>Max: 100.00 SD: 25.31</th>
</tr>
</thead>
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<tr>
<td>Field Uses Sprinkler Irrigation</td>
<td>SPRINK f†</td>
<td>Binary</td>
</tr>
<tr>
<td>Current or Most Recent Crop Grown on a Field</td>
<td>CROP f†</td>
<td>Categorical</td>
</tr>
<tr>
<td>Field Has Groundwater Access</td>
<td>GROUND f†</td>
<td>Binary</td>
</tr>
</tbody>
</table>

There are some limitations to the data. For example, the study lacks farm-level data and therefore cannot account for farm-level effects. However, fields nearer to each other are more likely to be owned by the same farm, and so the spatial regressions take some farm-level effects into account passively. The study also lacks any direct data on the wealth available to irrigation systems or individual farmers. That said, the area of an irrigation system is a proxy for the wealth and labor available to that irrigation system for operations and maintenance. Distinct patterns of natural resource use can be the product of distinct economic relationships (Kininmonth et al., 2017). Therefore, a dichotomous variable indicating whether an irrigation system was founded by the Spanish (ACEQUIA) is included. This provides socio-economic and demographic information, as those systems tend to be more collectivist, less capital intensive, physically smaller, less market oriented, utilize animal fertilizers, grow heirloom crops, and have historically been persecuted, oppressed, and excluded from governance processes (Rivera, 1998, Rodriguez, 2006). The use of sprinkler irrigation and infrastructure quality are also proxies for capital available to an individual farmer and ditch.
system, respectively, as well as the cost structure of the farmer who irrigates the field, an important feature in decision marking (Bell et al., 2016). Irrigation system area also correlates with the number of irrigators, a key variable important for the extent of and difficulty of solving collective action problems faced by irrigators. Finally, for systems using rotational delivery, the data lack information on the rotation itself – e.g. the location on the canal of each irrigator, the order in which they may take water, the duration of each farmer’s turn, etc.

Finally, over time, irrigation systems adopt rules based on the feedback irrigators receive from past performance (Ostrom, 2014). It could therefore be argued that the effects for different rules in use actually reflect past irrigation performance and/or the factors shaping past irrigation performance, not the current rules. However, the parsimonious explanation that arises from the data is that the causal explanations are straight-forward: the rules cause the outcomes. This is handled in more detail in Section B9 of Appendix B. Most importantly, the selection story and endogeneity argument presume that rules have real-time effects on performance; i.e. if performance responds to certain rules, irrigators will presumably alter rules to take advantage of these effects. Without that causal link, there is no selection pressure on the rules and there is no endogeneity. This study embraces that causal link, but argues that the feedbacks take too long and are too weak in the near-term to overwhelm the carefully designed analyses performed here. Irrigators report a highly cautious and slow-moving approach to institutional change at the level of the irrigation system, as well as the active influence of rules
on outcomes of the system (especially in drought and on the equality of head and tail-enders). Furthermore, because rules assessed in 2013 can’t have been shaped by performance in 2014, because the regressions account for other drivers of performance and rule choice, because the sample was stratified for important factors that drive performance and rule choice, and because of the content of the 60 interviews and other conversations with key stakeholders and informants, it is reasonable to interpret the results in a straight-forward way.

3.4.2. Analytical Methods

Following Gujarati and Porter (2009), OLS and logit regressions were run in R 3.2.2 for all years in the study period for three dependent variables; irrigated vs. fallowed (not irrigated) (logit), percentage irrigated (OLS), and NDVI (OLS). Using Primo et al. (2007) as a guide, the analysis is not a hierarchical model but instead uses OLS and logit regression with clustered standard errors at the level of the irrigation system. This is because the data exist only at two levels (field and irrigation system), the measure of interest is the average effect of the rules in use across systems, and fixed effects would obscure the rules in use. The models are run for each year as robustness. To specify the model, an iterative process was conducted between consulting theory and running correlations, pair-wise regressions, and analysis of variance to assess which of the available variables to include in the regressions. Variables that were not deemed sufficiently explanatory
or were not especially warranted by theory were excluded from the final regression.

The model without interactions takes the form:

\[ y_i = \beta_0 + \beta_1 SPRINK_i + \beta_2 CROP_i + \beta_3 GROUND_i + \beta_4 WATER_{SRC_i} + \beta_5 INC_i + \beta_6 SOUTH_i \\
+ \beta_7 ACEQUIA_i + \beta_8 INFRA_i + \beta_9 RES_i + \beta_{10} PERMAXACIRRAVE_i \\
+ \beta_{11} SLOPE_i + \beta_{12} WDPRIOR_i + \beta_{13} STRM\_DIST_i + \beta_{14} BASEACRES_i \\
+ \beta_{15} ACREPER_i + \beta_{16} DARES_i + \beta_{17} MULTD_i + \beta_{18} PERAVAFGAGE_i \\
+ \beta_{19} MONITOR_i + \beta_{20} LANDNEED_i + \beta_{21} SOIL_i + \beta_{22} CG2ROT_i \\
+ \beta_{23} DIV\_DIST_i + \beta_{24} SHR\_SRC_i + \beta_{25} ROT\_SRC_i + \beta_{26} AFDIV\_PERDacre_i \\
+ \beta_{27} SOLEUSER_i + \epsilon_i \]

Interactions between shortage sharing (SHR\_SRC) and rotational delivery (ROT\_SRC) were conducted to assess the first hypothesis. To assess the second hypothesis, a categorical variable with five categories (the four potential institutional configurations plus seven systems owned entirely by one farmer) was interacted with volume diverted by the irrigation system per irrigable unit area on that system (AFDIV\_PERDacre) and percent of the maximum field distance from the diversion (DIV\_DIST). South facing aspect (SOUTH), a ditch-level variable which captures the intensity of direct sunlight, was only included in models using NDVI as the dependent variable. Data for irrigation method (SPRINK), crop grown (CROP), and groundwater access (GROUND) were for the most recent observation for that field given the year under analysis (i.e. fields not irrigated were given the most recent data available, usually the previous year). Data for volume diverted per
irrigable unit area and percent average flow at the upstream gage (PERAVAFGAGE) were for the year under analysis. One ditch system lacked diversion volume data for 2014, and so it was excluded from the 2014 analysis.

Because percentage area irrigated and NDVI are censored variables, Tobit regressions were run to confirm the significance, size, and direction of the effects found using OLS. To explicitly account for spatial autocorrelation, spatial lag and spatial error models were also run (Bivand & Piras, 2015). These robustness checks confirmed the OLS and logit results. Because the OLS and logit results are easier to interpret, they are reported below.

3.5. Results

3.5.1. Hypothesis 1: Interaction Between Rotation and Shortage Sharing

Shortage sharing has a significantly different effect on outcomes under rotational delivery as compared to simultaneous delivery, and rotational delivery has a significantly different effect on outcomes under shortage sharing than under fixed allocations (p < 0.05). Figure 4 depicts the probability of a field being irrigated in 2012 under the four different institutional configurations. 2012 is representative of the overall results. The probability of being irrigated is shown here because irrigating a field reflects a large commitment on the part of an irrigator that is often made prior to the beginning of the irrigation season. It is therefore a more conservative measure of the influence of rules on outcomes.
Figure 3.4. A field's probability of being irrigated in 2012 under the four different institutional configurations evaluated: simultaneous delivery without shortage sharing, simultaneous delivery with shortage sharing, rotational delivery without shortage sharing, and rotational delivery with shortage sharing. Seven irrigation systems with only one farmer we excluded to ease interpretation. When rotating, shortage sharing has no significant effect on the probability that a field is irrigated in any year studied. When not rotating, shortage sharing significantly reduces the probability that a field will be irrigated. Conversely, when sharing shortage, rotation significantly improves a field's probability of being irrigated, whereas without shortage sharing rotation has a significantly negative effect in 2012 and 2014. Confidence bands are at 95%.
When rotating, shortage sharing has no significant effect on outcomes in any year studied for any dependent variable measured. That said, the predicted values for rotation and sharing is higher than rotation alone for the vast majority of years and dependent variables. When not rotating, shortage sharing significantly harms outcomes in all years studied for all dependent variables measured, supporting predictions. Conversely, when sharing shortage, rotation improves outcomes in all years studied for all dependent variables measured, as predicted. However, when there is no shortage sharing, rotation significantly harms the probability of being irrigated in 2012 and 2014. In other years and for other dependent variables, there is no significant difference, though the model’s predicted values are higher for simultaneous delivery and no shortage sharing in all years. This suggests agreement with the prediction that rotation without shortage sharing could have ambiguous effects.

3.5.2. Hypothesis 2: Institutions Interact with Degree of Scarcity and Field Distance

The second hypothesis is supported overall, though there are some circumstances where interactions are not significant and where results are unexpected. That said, the results illustrate similar trends across all outcome variables and across years, implying robust results. Table 3.2 provides detailed findings for each configuration.
Table 3.2. The main findings from the analysis of the second hypothesis. Overall, the most equitable arrangement is rotational delivery with shortage sharing and the least equitable arrangement is simultaneous delivery with shortage sharing. Depending on position on the ditch and water availability, rotational delivery with shortage sharing and simultaneous delivery without shortage sharing compete for the most productive arrangements overall. Each configuration is either the most or second most productive under some set of conditions consistently across years.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Head v. Tail Performance</th>
<th>Head v. Tail Marginal Productivity</th>
<th>Compared to Other Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sole Users</strong></td>
<td>Tail-end fields perform better than head-end fields at all levels of water availability.</td>
<td>Tail-end fields are more responsive to increases in water availability than head-end fields.</td>
<td>Tail-end fields tend to perform as well as the other institutional configurations across all levels of water availability. However, sole users are consistently the worst performing for head-end fields and mid-reachers across all levels of water availability.</td>
</tr>
<tr>
<td><strong>Simultaneous Delivery without Shortage Sharing</strong></td>
<td>At low levels of water availability, tail-enders perform better than head-enders, but as water availability increases head-enders outperform tail-enders.</td>
<td>Head-enders and mid-reachers are more responsive to increases in water availability than tail-enders, which eventually become essentially unresponsive to increases in water availability.</td>
<td>This institutional configuration is consistently the best or second-best performer for head-enders in moderate and minor and slight shortage. At lower levels of water availability, performance at the head-end becomes worst or second worst. However, this configuration is consistently the second-best performer at the tail-end for all levels of water availability.</td>
</tr>
<tr>
<td><strong>Simultaneous Delivery with Shortage Sharing</strong></td>
<td>Across all levels of water availability, the tail-end does worse than the head-end, especially in extreme and moderate shortage.</td>
<td>Head-enders and tail-enders are nearly equally weakly if at all responsive to increases in water availability.</td>
<td>Overall this configuration is the least responsive to increases in water availability compared to the others. This institutional configuration is consistently the second-best performer at the head end in extreme scarcity. But as water availability increases, performance at the head-end declines to worst or second-worst. Tail-enders fare even worse than this; at all levels of water availability, they perform worst or second worst.</td>
</tr>
<tr>
<td><strong>Rotational Delivery without Shortage Sharing</strong></td>
<td>There is no significant difference between head and tail-enders under this configuration at any level of water availability.</td>
<td>This configuration is the only instance of negative responsiveness – more water harms performance for both head and tail-enders.</td>
<td>Overall, in extreme scarcity, this is the highest performing configuration up and down the ditch. In moderate scarcity, performance drops to best or second best. But when shortage is minor and slight, both head and tail-end performance drops to worst or second worst.</td>
</tr>
<tr>
<td>Rotational Delivery with Shortage Sharing</td>
<td>There is no significant difference between head and tail-enders under this configuration at any level of water availability.</td>
<td>Fields from the head to the tail of the ditch are nearly equally responsive to increases in water availability.</td>
<td>This institutional configuration has the least variation across years and across different combinations of field distance and water availability. At the head-end, as water availability increases, performance improves from worst to second-best, while tail-end performance improves from third-worst to best; the head and tail-end share shortage roughly equally.</td>
</tr>
</tbody>
</table>

Rotational delivery mitigates inequality of irrigation performance between head-enders and tail-enders regardless of water availability and with or without shortage sharing. Rotational delivery without shortage sharing improves marginal productivity at the tail-end but is easily overwhelmed by increases in water availability without shortage sharing, leading to negative marginal productivity (i.e. more water decreases crop production). This exceeds predictions, which expected no or low positive marginal productivity and suggests physical damage. Shortage sharing increases marginal productivity under rotation but diminishes marginal productivity to near zero under simultaneous delivery, especially at the tail-end. Shortage sharing also makes inequality worse under simultaneous delivery as compared to under rotation, especially in extreme shortage at the tail-end. The weakest differences between performance of the different configurations emerge at the head-end under extreme scarcity, with the tail-ends under minor and slight scarcity generating the largest differences in performance between institutional configurations. Figure 3.5 and Figure 3.6 illustrate these results through predicted
2012 NDVI using an interaction between rules in use, field distance from diversion, and volume diverted per unit area.

**Figure 3.5.** Head vs tail-end performance at different levels of water availability. Each panel illustrates this relationship between a field’s distance from the diversion structure and NDVI for a different value of volume diverted per unit area, corresponding to extreme, moderate, and minor shortage (the 10th, 50th, and 80th percentiles, respectively, of the 2011-2014 average volume diverted per unit area of the system). SDNS = Simultaneous Delivery with No Sharing; RNS = Rotation with No Sharing; SDS = Simultaneous Delivery and Sharing; RS = Rotation and Sharing; SOLE = Sole User. Confidence bands are at 90%.

Figure 3.5 illustrates performance as one moves from the head-end to the tail-end of the system for different levels of water availability, while Figure 3.6 illustrates the marginal productivity of water at different points along the irrigation network. For these results, seven irrigation systems owned by only one farmer are included as counterfactuals to systems reliant on collective action. Results for NDVI
are given here because NDVI represents a proxy for the other outcomes: lower NDVI values also correspond to lower irrigated area, including no irrigation. NDVI represents a better approximation of total crop growth, and therefore income and potential for subsistence, than irrigated area because NDVI also includes information about the intensity of crop growth and therefore the weight of sellable or consumable crop. In brief, NDVI gives a sense of both how extensive and intensive irrigation was.

Figure 3.6. Marginal productivity of water at different distances from the diversion. Each panel illustrates the relationship between volume diverted unit area and NDVI for a different value of field distance from diversion, representing 5, 50, and 95 percent, respectively, of the maximum field distance of its irrigation system. This corresponds to head-enders, mid-reachers, and tail-enders. SDNS = Simultaneous Delivery with No Sharing; RNS = Rotation with No Sharing; SDS = Simultaneous Delivery and Sharing; RS = Rotation and Sharing; SOLE = Sole User. Confidence bands are at 90%.
3.6. Discussion

This study advances the literature by considering the combined effects on irrigation performance of shortage sharing and delivery method. There are numerous studies that separately investigate shortage sharing (D'Exelle et al., 2013; He et al., 2012; Torell and Ward, 2010; Ward et al., 2013) and rotation (Abdullaev et al., 2006; Janssen et al., 2012; Turral et al., 2002). Yet complicating this literature, there is not agreement as to what constitutes shortage sharing. D'Exelle et al. (2013) investigated instances where head-enders forego diversions with the intention of enabling tail-enders to irrigate (thus reducing the head-ender diversions disproportionately), finding that while this reduced efficiency, it improved equality. Ward et al. (2013) and Torell and Ward (2010) assessed various shortage sharing arrangements, finding that an equal percentage reduction in diversions by all irrigators was flexible, easily understood, and enhanced crop production as compared to shortage arrangements that applied unequal risk burdens. He et al. (2012) also studies several mechanisms of shortage sharing under Prior Appropriation in Alberta, Canada where changes to water allocations were made through various inflexible rules as well as markets. They found that all modes of shortage sharing were efficiency improvements over Prior Appropriation, with market exchanges being the most efficient (these findings were for inter-system sharing, not intra-system sharing as in the present study). The overall message from the literature regarding shortage sharing is that it is beneficial, especially when it is congruent with contributions to system maintenance, allocates shortage
risk equitably, and is agreed upon in a transparent manner between all members of the irrigation system (Bernard et al., 2013; Dayton-Johnson, 2000; Torell and Ward, 2010; Ward et al., 2013). However, the present study draws a contrasting finding; shortage sharing can actually result in worse performance overall, and for tail-end users in particular, if rotation is not also employed. However the present study finds that shortage sharing produces benefits overall when coupled with rotational delivery.

As to rotation, the literature has largely found that rotation accomplishes the goals it is implemented to achieve: it improves equality between the head-end and tail-end (Abdullaev et al., 2006; Turral et al., 2002). Indeed, irrigators in the SLV directly stated in interviews that this was the intention of rotation. While Janssen et al. (2012) does not make this finding in an experimental setting, the rotational delivery mechanism was not accompanied by enforcement of any maximum diversion duration or amount, was not negotiated by the irrigators, and the effect of rotation was not the focus of the study. Additionally, rotation was selected by 2/3 of the experimental groups of real-world irrigators in Janssen et al. (2012), possibly because irrigators understood that rotation is effective and equitable. Similar to other studies, the findings of the present study do not find that rotation is necessarily efficiency enhancing, only that under a well-functioning rotational system the most vulnerable irrigators, tail-enders, are spared from the worse consequences of drought, particularly when shortage sharing is also allowed.
The fundamental contribution of this study is that the effects of delivery and allocation rules differ depending on their configuration. Baggio et al. (2016) finds configurations important when looking at the design principles offered by Ostrom (2005), however this study finds configurations important for specific operational rules in use. Indeed, the impact of the same combinations of delivery and shortage sharing rules can differ between head-enders and tail-enders, and even these effects are conditional on the degree of water shortage.

The policy implications of these findings are not prescriptive. The answer to the question, “Which rule is best?” depends on which other rules are place. The answer to the derivative question, “Which configuration of rules is best?” also depends a great deal on where the farmer asking the question is located on the irrigation system and how much water is available to that system. Therefore, water managers and irrigators alike should weigh hydrologic context, equity, and social norms heavily in determining which rules to experiment with and adopt.

3.7. Chapter Conclusion

Optimality depends strongly on normative assessments of equity (Ingram et al., 2008). This study implies that the optimal choice of institutions depends strongly on the normative, infrastructural, and hydrologic conditions of a given irrigation system over period of many years. These findings have implications for an era of climate change, wherein irrigated agriculture will face serious challenges (FAO, 2012; Kramer et al., 2017; Lee et al., 2014; Turral et al., 2011) and
institutional changes have been proposed as potential adaptations (Huntjens et al., 2012). Moreover, the highly contextual influence of the rules in use under investigation highlight the configurational relationships between rules in use (Baggio et al., 2016), further demonstrate institutional interactions with biophysical context (Cody, 2018b), caution against panaceas in water resource management (Meinzen-Dick, 2007), and support a diagnostic approach to institutional analysis (Ostrom, 2007). Because of the delicate distribution of individual and group costs and benefits (Bell et al., 2016; McCord et al., 2017; Pérez, et al., 2016); heterogeneous market integration (Kininmonth et al., 2017); and divergent hydrology, infrastructure, ecological context, and institutions, “Institutional change needs to be seen as an organic process, building on existing norms and practices, rather than as an exercise in social engineering” (Meinzen-Dick, 2014:23).

That said, this study shows rotational delivery with shortage sharing as the most robust institutional configuration examined. In addition to generating the most equality between head-enders and tail-enders overall, this configuration has positive marginal productivity up and down the canal at all levels of water availability, and therefore represents a “safe bet” under uncertain water supplies. This configuration also appears to be well suited for systems large and small, growing a wide array of crops, with different social and cultural norms, and various technological and infrastructural mixes. However, it does require sufficient resources and labor to engage in the necessary negotiations, monitoring, and, presumably, sanctioning. It may also have some hydrologic and agronomic
limitations in severe shortage, with water being spread too thinly. Perhaps this is why, in the Hispanic *acequia* tradition in the URGB where rotation and shortage sharing were traditionally practiced, extreme shortage was met by growing crops on only the best land, with the surplus shared among the community. Of course, there are limitations to this study, and future work should include direct measures of welfare, norms, identify farm units, use simulations, and investigate different water rights and climatic regimes. The next chapter, Chapter 4, interrogates how norms and divergent water rights regimes influence performance and shape institutional choice, and so addresses these limitations to some degree.
4.1. Norms, Rules, and Performance of Self-Governing Irrigation Systems

Cultural norms are an important and under-studied factor in the management of user-governed CPRs such as irrigation systems (Poteete et al., 2010; Vollan & Ostrom, 2010; Vollan et al., 2013). Norms are codes of behavior which are socially enforced as opposed to legally enforced; there is no prescribed punishment for violating them, but violators usually face some form of informal social punishment (Ostrom, 2000). Punishments such as public shaming and social exclusion apply costs, ultimately offsetting important benefits drawn from the group such as access to resources, social status, and networks (Creanza et al., 2017; Richerson & Boyd, 2001; Richerson et al., 2002; Waring et al., 2017). Social sanctions have been shown to be highly influential for human behavior (Falk et al., 2012). Additionally, norms can become internalized, leading to innate psychological preferences for certain behaviors, even absent external incentives (Gavrilets & Richerson, 2017; Ghate et al., 2013). From the evolutionary perspective of MLS Theory, internalized norms have important benefits for groups in their contests
with other groups (Richerson & Boyd, 2001; Richerson et al., 2002; van den Bergh & Gowdy, 2009; Waring et al., 2017). Norms can be very strongly held, though even new entrants to a CPR regime with different norms can quickly learn and adhere to new ones (Smith, 2016). Therefore, norms matter because they shape the decisions made by CPR users (Ostrom, 2000).

From a governance perspective, norms influence the efficacy of external interventions and shape how local resource users respond to shocks, including price fluctuations, climate-related events, and external governance interventions (Kinzig et al., 2013; Rode et al., 2015; Roth et al., 2015). Without a better understanding of how norms and multiple sources of authority work in a CPR, governance actors may make decisions that undermine the sustainability of CPRs and harm adaptation to climate change (Brunsa et al., 2001; Hoogesteger, 2015; Meinzen-Dick & Pradhan, 2002; Skjølsvold, 2010). In the case of irrigation systems, this could lead to food insecurity, mass migration, and conflict (Gleick, 2014; Meinzen-Dick, 2014). However, testing norms in the field and through experiments is difficult and there is insufficient empirical evidence to make robust predictions of outcomes based on differences in norms (Poteete et al., 2010). Evidence of the role norms might play in climate change adaptation is also lacking, although some suggestive studies exist (Arunrat et al., 2017; Chhetri et al., 2012; Laube et al., 2012).

Given this, what is the role of norms in the adoption of rules and technologies by self-governing irrigation systems and what is their impact on irrigation performance in drought? Theory would predict: (1) internalized norms shape
institutional and technological configurations, and (2) the same institutional and technological configuration will produce different outcomes depending on the underlying norms of the population. This paper investigates how norms influence irrigation systems by utilizing data from a stratified, semi-random sample of 71 irrigation systems in the URGB of the United States. Two distinct waves of colonization from the 17th through the 20th centuries by Europeans – first by Hispanic irrigators who mingled their practices with Native Americans and later by Anglo irrigators who imposed their legal and market system on Hispanics to varying degrees – and a drought from 2011-2014 allow for tests of how norms work under similar rules.

4.2. The Evolution and Influence of Norms in the URGB

4.2.1. Theoretical Basis for the Evolution of Cooperation in Groups

Behavior motivated by norms is relevant for irrigation because collective action is influenced by norms and is necessary to build, operate, and maintain irrigation systems (Ostrom, 2000). From the perspective of CPR Theory, norms may be more or less other-regarding and communitarian (i.e., pro-social, typified by altruism) or self-centered and individualistic (i.e., anti-social, typified by rational egoism), generating cooperative or competitive behavior (Poteete et al., 2010; Vollan & Ostrom, 2010; Waring et al., 2017). The cultural evolution and CPR literature has increasingly relied on MLS Theory (Creanza et al., 2017; Richerson & Boyd, 2001; Richerson et al., 2002; Waring et al., 2017; Wilson et al., 2013), and has established
that norms, operationalized as internalized heuristics of expected behavior, can partly explain boundedly rational individual motivations to act collectively (Carballo et al., 2014; Poteete et al., 2010; Rustagi et al., 2010). Drawing on this literature, this study conceives of cooperative and competitive behavior as existing along a continuum, ranging from pure altruism to pure rational egoism (Ostrom, 2000). Therefore, where evidence of cooperative norms is lacking, competitive norms can be said exist in greater proportion. For example, a cooperative norm in the irrigation context would favor contributions of labor and materials for system maintenance, whereas a competitive norm would favor withholding labor and materials. Therefore, in the absence of defined rules requiring contributions to maintenance, evidence of higher contributions to maintenance would be evidence of more cooperative norms.

Under the standard assumptions of MLS theory, selection favors competition, because competitive norms lead individuals to maximize their net benefits at the expense of others (Nowak, 2006). However, cooperative norms can evolve when individuals garner net benefits – either materially, psychologically, or through elevated status and expanded mate choice – from actions that benefit others and are costly in the short term (Ostrom, 2000; Poteete et al., 2010). For example, punishing non-cooperators is costly to the punisher in the short-term, but may bring long-term, group-level benefits which extend to the individual and outweigh the short-term individual costs (Rustagi et al., 2010; van den Bergh & Gowdy, 2009). Individuals may also be willing to pay material costs to promote the group interests
in order to gain recognition and status. Conversely, competitive norms can evolve where greater net benefits can be garnered through behaviors which do not regard the wellbeing of others (Nowak, 2006). In the irrigation context, high levels of individual material wealth, high system turnover (and thus a low likelihood of reputation development or kin interactions), and geographic hierarchies created by the canal network may make social relationships relatively unimportant for individual performance, leading to more selfish behavior. As a general matter, cooperative norms evolve in contexts where collective action generates net benefits for individuals due to kin relationships, direct and indirect reciprocity, structured populations, or group-level interactions (Creanza et al., 2017; Nowak, 2006; van den Bergh & Gowdy, 2009; Wilson et al., 2013).

4.2.2. Evolving Cooperative Norms through Historical Selection Pressures

Despite vast individual and subgroup variation (Lamba & Mace, 2011), people who derive from different cultural groups, or who experience divergent histories, may internalize different norms (Henrich, 2014; Prediger et al., 2011). There are many contextual mechanisms which select for norms of cooperation or competition (Creanza et al., 2017; Gavrilets & Richerson, 2017; Gintis, 2011; Richerson et al., 2002; van den Bergh & Gowdy, 2009; Waring et al., 2017). Such mechanisms can vary by group to the extent that these groups’ contexts have differed over long periods of time, leading to the transmission and internalization of different norms (Henrich, 2014; Prediger et al., 2011; Talhelm et al., 2014; Tucker &
Taylor, 2007). Four contextual features of importance for this study are used to explain the internalization of cooperative or competitive norms.

First, functionalist approaches to human behavior imply that whether irrigation produces crops for subsistence or for the market will shape the norms irrigators internalize over time (Henrich, 2014; Tucker & Taylor, 2007; Waring et al., 2017). In a competitive market context, success in the market generates wealth; enables the purchase of labor, tools, and calories; and improves status, attracts mates, and supports offspring (Creanza et al., 2017; Tucker & Taylor, 2007). In such a context, individuals who internalize competitive norms will outperform those who do not, leading to increased horizontal and vertical transmission of competitive norms. Subsistence economies, in contrast, necessitate increased cooperation (Ghate et al., 2013); ensuring the survival of community members is paramount, since it is the community from which wealth, labor, tools, calories, and mates are drawn (Carballo et al., 2014; Richerson & Boyd, 2001; Richerson et al., 2002). Therefore, irrigators who inhabit a subsistence economy are more likely to internalize and transmit cooperative norms.

Second, when limiting resources cannot easily be monopolized using available technologies – such as when resources are large, physically diffuse, or fugitive and when mechanized equipment is unavailable – it is costly to compete with others by attempting to exclude them, favoring cooperation (Jaeggi et al., 2016; Ostrom, 1990; Schlager et al., 1994). Third, when hierarchy is low – whether due to relatively equal coalition sizes, an equal distribution of technologies, or the legal requirement
to hold property in common – cooperation can be favored due to the costliness of competition between relative equals (Jaeggi et al., 2016; Waring & Bell, 2013). And fourth, in interactions between groups, a group comprised of competitors will undermine their collective efforts, leading to worse outcomes for all in the group compared to groups of cooperators capable of achieving higher levels of collective action (Makowsky & Smaldino, 2016; Richerson et al., 2002; van den Bergh & Gowdy, 2009; Waring et al., 2017).

4.2.3. Brief History of Hispanic and Anglo Irrigation in the URGB

In light of this, the URGB is an ideal place to test the influence of norms. Hispanic irrigators using the acequia system have occupied the study area (Figure 4.1) since the late 1600s (Rivera, 1998). Acequias are a common property irrigation system that has evolved over hundreds of years, if not thousands, primarily for subsistence purposes (Rodriguez, 2006). Originating in West Asia and North Africa and brought to the Iberian Peninsula following the decline of the Roman Empire, the Spanish later established acequias in their American colonies, mingling them with subsistence Native American irrigation methods (Hutchins, 1928; Rodriguez, 2006). In the 1870s, market-oriented Anglo-American homesteaders began to colonize the study area, leading to cash replacing barter and greater technological and market intensification and infrastructure, such as rail and banking. Consequently, acequia communities of this area experienced different degrees of Anglo-American influence and can be categorized accordingly (Table 4.1).
Figure 4.1. Colonial irrigation, Counties, and major streams in the URGB.
Table 4.1. Historical origins and legal context of URGB irrigation systems. The sample contains one *acequia* in Rio Grande County, but is included within Conejos County for simplicity.

<table>
<thead>
<tr>
<th>Irrigation System Traits</th>
<th>Taos <em>Acequias</em></th>
<th>Costilla <em>Acequias</em></th>
<th>Conejos <em>Acequias</em></th>
<th>Anglo Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earliest Irrigation</td>
<td>1670s</td>
<td>1850s</td>
<td>1850s</td>
<td>1870s</td>
</tr>
<tr>
<td>Recognition in US Law</td>
<td>1850s</td>
<td>2000s</td>
<td>2000s</td>
<td>1870s</td>
</tr>
<tr>
<td><em>De Facto</em> Water Rights in Past Between Systems</td>
<td><em>Repartimiento</em></td>
<td><em>Repartimiento</em></td>
<td><em>Repartimiento</em></td>
<td>Prior Appropriation</td>
</tr>
<tr>
<td><em>De Facto</em> Water Rights in Present Between Systems</td>
<td><em>Repartimiento</em></td>
<td>Prior Appropriation</td>
<td>Prior Appropriation</td>
<td>Prior Appropriation</td>
</tr>
<tr>
<td><em>De Facto</em> Water Rights in Past Within Systems</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Pro-Rata Shares</td>
</tr>
<tr>
<td><em>De Facto</em> Water Rights in Present Within Systems</td>
<td>Need and Prior Use</td>
<td>Need and Prior Use</td>
<td>Pro-Rata Shares</td>
<td>Pro-Rata Shares</td>
</tr>
<tr>
<td>Irrigated Land Tenure</td>
<td>Vara Strips</td>
<td>Vara Strips</td>
<td>PLSS</td>
<td>PLSS</td>
</tr>
<tr>
<td>Sample Size</td>
<td>18</td>
<td>12</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>Major Crops</td>
<td>Alfalfa, Pasture, Gardens</td>
<td>Alfalfa, Pasture, Grain</td>
<td>Alfalfa, Pasture, Grain</td>
<td>Alfalfa, Pasture, Potato, Grain</td>
</tr>
<tr>
<td>Percent with Surface Reservoir Access</td>
<td>11</td>
<td>33</td>
<td>44</td>
<td>48</td>
</tr>
<tr>
<td>Irrigation System Hectares</td>
<td>Min: 8.3</td>
<td>Median: 69.2</td>
<td>Mean: 113.2</td>
<td>Max: 558.6</td>
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<tr>
<td></td>
<td>Median: 11.8</td>
<td>Median: 107.8</td>
<td>Mean: 925.1</td>
<td>Max: 8036.8</td>
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<tr>
<td></td>
<td>Mean: 130.7</td>
<td>Std. Dev.: 2272.5</td>
<td>Std. Dev.: 1302.4</td>
<td>Std. Dev.: 12280.3</td>
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<tr>
<td>Average Farm Hectares on Irrigation System</td>
<td>Min: 0.4</td>
<td>Median: 1.0</td>
<td>Mean: 1.9</td>
<td>Max: 7.1</td>
</tr>
<tr>
<td></td>
<td>Median: 1.2</td>
<td>Median: 27.5</td>
<td>Mean: 43.5</td>
<td>Max: 267.9</td>
</tr>
<tr>
<td></td>
<td>Mean: 224.0</td>
<td>Std. Dev.: 130.7</td>
<td>Std. Dev.: 50.8</td>
<td>Std. Dev.: 176.4</td>
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<tr>
<td>Days per Year of Normal Surface Water Availability to Irrigation System</td>
<td>Min: 46</td>
<td>Median: 105</td>
<td>Mean: 182.5</td>
<td>Max: 213</td>
</tr>
<tr>
<td></td>
<td>Median: 128</td>
<td>Median: 182.5</td>
<td>Mean: 173.3</td>
<td>Max: 213</td>
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<tr>
<td></td>
<td>Mean: 145.4</td>
<td>Std. Dev.: 34.5</td>
<td>Std. Dev.: 71.5</td>
<td>Std. Dev.: 71.5</td>
</tr>
</tbody>
</table>

The most consequential Anglo influences on *acequias* are with respect to *de facto* water rights and land tenure. After being founded by the Spanish using distinct institutions, the United States imposed both the grid-based Public Land
Survey System (PLSS) and private water rights in the form of the Prior Appropriation Doctrine on most counties (Rivera, 1998). However, the PLSS was not imposed in Taos or Costilla counties, allowing for the continuation of the distinct “long lots” (vara strips) and the corresponding hydrologic and social relationships of the acequias. Private water rights were not *de facto* imposed in Taos (Cox, 2010; Smith, 2014), whereas in Colorado acequias and Anglo systems are indistinguishable from each other between 1984-2014 with regards to the influence of Prior Appropriation on water diversion duration and amount and irrigated area (Cody, 2018b). Importantly, the vast majority of acequias in Taos and Costilla counties continue to allocate water within their irrigation systems using traditional negotiated methods based on need and prior use; once diverted into the acequia, water is the *de facto* common property of irrigators using an acequia in those counties. However, due in part to the disruption of the long lots and Colorado’s administration of the Conejos River under the Rio Grande Compact, the vast majority of acequias in Conejos County allocate water within their irrigation systems based on individual farmers’ private water rights. Despite legislation written by acequia leadership passed in 2009, acequias in Colorado historically lacked legal recognition, creating a context where their norms and traditional practices conflicted with law (Davidson & Guarino, 2015; Lindner, 2012; Rivera, 2010). In New Mexico, in contrast, acequias were integrated into Territorial and later State law and still practice *repartimiento*, the negotiated sharing of water between acequias not based on Prior Appropriation (Cox, 2010; Smith, 2014).
Therefore, in Taos, water is *de facto* common property both before and after being diverted. On Anglo systems, water is considered private property both before and after being diverted both normatively and legally (Goldstein & Hudak; 2017).

4.2.4. Summary of Reasoning for Differences in Internalized Norms between Hispanic and Anglo Irrigators

Literature, history, and theory suggest that irrigators on *acequias* have more heavily internalized norms of cooperation, while irrigators on Anglo systems have more heavily internalized norms of competition. Recent studies of *acequias* (Hicks & Peña, 2003; Turner et al., 2016; Gunda et al., 2018) identify underlying cooperative norms as essential to their function, while recent studies of Anglo farmers in the study region (Cody et al., 2015; Smith et al., 2017; Smith, 2018a) identify underlying competitive norms that have required extensive interventions to overcome in efforts to halt a tragedy of the commons in groundwater. Peña (2017) has also identified direct normative conflicts between Anglos and Hispanics in Costilla county related to land and water rights.

Among Hispanics, organizations such as the mutual aid society *La Sociedad Protección Mutua de Trabajadores Unidos* (The Society for the Mutual Protection of United Workers) and the lay religious society *Los Penitentes* (The Penitent Ones) reinforce trust and reciprocity, provide social insurance and protection, and promote a selfless moral character monitored by God (Cox et al., 2014). They also provide opportunities to establish a cooperative reputation and reinforce other-regarding
preferences. At the same time, annual traditions among acequias such as *La Limpieza* (The Cleaning), where all land owners and their families participate directly in ditch maintenance, and *La Día de San Isidro* (The Day of Saint Isidro), a parade traditionally led by a priest and followed by a feast which marks the beginning of irrigation season and celebrates the patron saint of farmers, similarly reinforce identification with the community, reciprocity through mutual provision of labor and food, and links between selfless moral character, behaviors around water, and piety. Anglos in the study area have no such community traditions around ditch maintenance or the start of irrigation season. These functions are generally achieved through the centralized purchase of labor and supplies and a proclamation from the Office of the State Engineer, respectively, and can be accomplished with minimal interpersonal interaction for greater economic efficiency.

The essence of the evolutionary argument is that the greater preponderance of cooperative norms among acequias derives from their distinct origins in subsistence economies, and because for hundreds of years their technologies, laws, and community structure made it relatively more challenging for individuals to monopolize resources and attain substantially increased bargaining power. For example, Hispanic farmers traditionally split land between their sons, rather than consolidating their holdings with the eldest son like Anglos. Hispanic irrigators also lacked much military protection and needed to act collectively to survive Native American raids and defend their land against Anglo colonization (Rivera, 2010). Conversely, Anglo’s orientation towards markets, private property, and
technological intensification of agriculture made it relatively easier to monopolize resources, generate stronger hierarchies, and reward competitive behavior. Anglos also benefitted from substantial military protection, and therefore did not need to organize as a group for defense to the same extent as Hispanics.

4.2.5. Open Questions on the Effects of Norms on Irrigation Performance

The role of internalized norms in determining irrigation performance is not entirely clear (Poteete et al., 2010). However, norms have been observed to affect behavior important for irrigation where enforced rules are also in place. For example, norms can supplant rules (Ostrom, 2000). An internalized norm against anti-social behavior, such as stealing water, may make a rule unnecessary, even if a rule against stealing is still technically enforceable (Kinzig et al., 2013). In contrast, enforcement of a rule against stealing may reduce stealing if the norm against it is not internalized, and cooperation is merely conditional on the assurance that others are also not stealing (Rustagi et al., 2010). In contrast, norms can be crowded-out by rules, where a rule undermines intrinsic motivations and leads to worse outcomes (Kinzig et al., 2013; Rode et al., 2015). For example, enforcement of a rule against stealing could release irrigators from internalized moral responsibility, making getting caught stealing, as opposed to stealing itself, the bad result (Rode et al., 2015). Such a rule could also be seen as a sign of distrust, leading irrigators to conclude that they will be the “sucker” if they don’t steal (Ostrom, 2000). In contrast, crowding-in, or reinforcing, a norm could occur if a rule is seen as a
reminder to do the right thing (Rode et al., 2015). On balance, the literature implies that individuals who are more intrinsically competitive will likely respond with more cooperative behavior if rules enforcing cooperative behavior are in place (Ostrom, 2000; Rustagi et al., 2010), while individuals who are more intrinsically cooperative will likely respond with little to no increase in cooperative behavior and may even show declines due to crowding-out (Kinzig et al., 2013; Rode et al., 2015). This appears to be supported in the field, where externally imposed rules that are not congruent with local cooperative norms produce worse commons management (Hoogesteger, 2015; Kamran & Shivakoti, 2013; Ostrom, 2000; Vollan et al., 2013).

4.2.6. Expectations of Internalized Norms in the URGB’s Irrigation Systems

To answer the main questions regarding the role of norms in the adoption of rules and technologies and norms’ impact on irrigation performance in drought, multiple hypotheses were generated (Table 4.2). The presence of a monitoring agent was chosen to test these hypotheses because of its global ubiquity (Mabry, 1996; Ostrom, 1990), central importance to commons management (Cox et al., 2010), and because its major function is to encourage cooperative behavior on the irrigation system. In this study, monitoring agents are usually peers elected by irrigators. Monitors are tasked with administering water based on the de facto water rights established between irrigators on the same system, checking the water use of irrigators, and enforcing rules when they are violated. Monitors are also often
leaders of the irrigation system, settling disputes, coordinating maintenance, and interfacing with other irrigation systems and government entities.

### Table 4.2. Hypotheses, rationales, and supporting literature.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Rationale</th>
<th>Key Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>H1</strong>: Hispanic irrigation systems will adopt rules and technologies that promote equality and collective action at higher frequencies than Anglo systems.</td>
<td>Historical selective pressure for cooperative norms drives their internalization, and these norms then drive the adoption of rules and technologies that promote collective action and deter competitive behavior.</td>
<td>Carballo et al., 2014; Gavrilets &amp; Richerson, 2017; Ghate, et al., 2013; Henrich, 2014; Jaeggi et al., 2016; Makowsky &amp; Smaldino, 2016; Nowak, 2006; Prediger et al., 2011; Richerson &amp; Boyd, 2001; Richerson et al., 2002; Talhelm et al., 2014; Tucker &amp; Taylor, 2007; van der Kooij et al., 2015</td>
</tr>
<tr>
<td><strong>H2</strong>: Where rules are congruent with competitive norms, as with Anglo systems, monitoring agents will reduce water use violations, improve average crop production, and decrease crop production equality.</td>
<td>Internalized norms of competition will amplify the deterrent effect of enforcement, and monitoring agents enforcing competitive rules will generate higher average crop production at the expense of the equality of crop production.</td>
<td>Cody et al., 2015; Kinzig et al., 2013; Ostrom, 2000; Rode et al., 2015; Rustagi et al., 2010; Smith et al., 2017; Smith, 2018a</td>
</tr>
<tr>
<td><strong>H3</strong>: Where rules are congruent with cooperative norms, as with acequias from Costilla and Taos, monitoring agents will have no effect or a negative effect on water use violations, decrease average crop production, and increase crop production equality.</td>
<td>Internalized norms of cooperation will render the deterrent effect of enforcement negligible or deleterious due to crowding-out, monitoring agents enforcing cooperative rules will generate more equal crop production at the expense of average crop production due to crowding-in.</td>
<td>Falk et al., 2012; Gunda et al., 2018; Kinzig et al., 2013; Ostrom, 2000; Rode et al., 2015; Rustagi et al., 2010; Smith, 2014; Turner et al., 2016</td>
</tr>
<tr>
<td><strong>H4</strong>: Where competitive rules are incongruent with cooperative norms, as with acequias from Conejos, monitoring agents will increase water use violations, reduce average crop production, and reduce crop production equality.</td>
<td>Attempts to enforce rules counter to norms will generate conflict as irrigators actively oppose the rules and as monitoring agents fail to effectively enforce water allocations, leading to a breakdown of collective action.</td>
<td>Ostrom, 2000; Rode et al., 2015; Kamran &amp; Shivakoti, 2013; Vollan et al., 2013; Hoogesteger, 2015</td>
</tr>
</tbody>
</table>
4.3. Methods: Using Surveys and Spatial Data to Assess the Role of Norms in the Form and Function Self-Governing Irrigation Systems

This observational study tests whether irrigation systems founded as *acequias* differ meaningfully in their structure and function from those founded by Anglos. *Acequia* status was assigned to systems founded prior to 1880 and carrying a Spanish name (e.g. *la del rio*, *Salazar ditch*, *acequiacita*). Key data sources included: Colorado Department of Natural Resources’ (DNR) Decision Support Systems, U.S. Geological Survey (USGS), U.S. Natural Resources Conservation Service (NRCS), New Mexico’s Office of the State Engineer (OSE), Taos County Assessor (TCA), GoogleEarth Engine, and the 2010 US Census. Institutional, agronomic, hydrologic, and other data were gathered from a stratified, semi-random sample of 71 irrigation systems in 2013 (Table 4.3). All analyses have been informed by qualitative data collected through key stakeholder interviews, primary source analysis, and direct observation during site visits from 2012-2017.

<table>
<thead>
<tr>
<th>Table 4.3. Variable names, data sources and descriptive statistics. Appendix C Table C.1 provides measurement methods.</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable Name</strong></td>
<td><strong>Data Source</strong></td>
<td><strong>Descriptive Stats</strong></td>
</tr>
<tr>
<td><strong>Independent Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Acequia</em></td>
<td>OSE; DNR</td>
<td>N: 71 PERCENT <em>ACEQUIA</em>: 67.6</td>
</tr>
<tr>
<td>Ditch Type</td>
<td>OSE; DNR</td>
<td>N: 71 ANGLO: 23 OTHER COLORADO <em>ACEQUIAS</em>: 18 COSTILLA <em>ACEQUIAS</em>: 12 TAOS <em>ACEQUIAS</em>: 18</td>
</tr>
<tr>
<td>Monitoring Agent</td>
<td>2013 Survey</td>
<td>N: 71 PERCENT WITH MONITOR: 71.2</td>
</tr>
<tr>
<td><strong>Control Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Survey Year</td>
<td>Sample Size</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Days Water is Normally Available</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Rotate Water Delivery in Scarcity</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Normally Rotate Water Delivery</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Labor Required</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Inter-System Sharing Arrangements Present</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>High Capacity Groundwater Wells Present</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Vegetable Gardens Present</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Long Lots Present</td>
<td>2013 Survey</td>
<td>N: 71</td>
</tr>
<tr>
<td>Change Water Allocations in Scarcity</td>
<td>2013 Survey</td>
<td>N: 71</td>
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<tr>
<td>Percent Hispanic</td>
<td>2010 US Census</td>
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<tr>
<td>Water Not Allocated by Private Rights</td>
<td>2013 Survey</td>
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<tr>
<td>Dependency Ratio</td>
<td>2010 US Census</td>
<td>N: 71</td>
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<tr>
<td>Hold Annual Meeting</td>
<td>2013 Survey</td>
<td>N: 71</td>
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<tr>
<td>Percent Renters</td>
<td>2010 US Census</td>
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<td>Percent Hydric Soils</td>
<td>NRCS</td>
<td>N: 71</td>
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<tr>
<td>---------------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>Min: 0.0</td>
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</tr>
<tr>
<td></td>
<td>Med: 17.1</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td>Max: 63.3</td>
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<td></td>
<td>SD: 16.1</td>
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<thead>
<tr>
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<tr>
<td></td>
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<tr>
<td></td>
<td>Med: 38.9</td>
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<td></td>
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<td></td>
<td>Max: 669.9</td>
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<table>
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<tbody>
<tr>
<td></td>
<td>Min: 8.3</td>
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</tr>
<tr>
<td></td>
<td>Med: 256.3</td>
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</tr>
<tr>
<td></td>
<td>Mean: 3036.8</td>
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</tr>
<tr>
<td></td>
<td>Max: 47475.7</td>
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</tr>
<tr>
<td></td>
<td>SD: 7850.4</td>
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</table>

<table>
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<th>Sprinkler Irrigation Present</th>
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<tbody>
<tr>
<td></td>
<td>PERCENT SPRINKLER IRRIGATED: 46.5</td>
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<table>
<thead>
<tr>
<th>Bylaws Present</th>
<th>2013 Survey</th>
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<tbody>
<tr>
<td></td>
<td>PERCENT WITH BYLAWS: 67.6</td>
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<table>
<thead>
<tr>
<th>US State</th>
<th>2013 Survey</th>
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<tr>
<td></td>
<td>PERCENT NEW MEXICO: 25.4</td>
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</table>

<table>
<thead>
<tr>
<th>Per Capita Voting Present</th>
<th>2013 Survey</th>
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<tbody>
<tr>
<td></td>
<td>PERCENT VOTE PER CAPITA: 78.9</td>
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<table>
<thead>
<tr>
<th>Dependent Variables</th>
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<tr>
<td>Frequency of Water Use Violations</td>
<td>Never: 31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than Once Per Year: 19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Once Per Year: 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than Once Per Year: 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Often: 2</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>2011-2014 Average System Average NDVI in July</th>
<th>GoogleEarth Engine; USGS Landsat</th>
<th>N: 71</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min: 0.0859</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Med: 0.4499</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean: 0.4316</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max: 0.6434</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD: 0.1199</td>
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</table>

<table>
<thead>
<tr>
<th>2011-2014 Average System Spatial Standard Deviation of NDVI in July</th>
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<tbody>
<tr>
<td></td>
<td>Min: 0.0431</td>
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<tr>
<td></td>
<td>Med: 0.2081</td>
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</tr>
<tr>
<td></td>
<td>Mean: 0.2080</td>
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</tr>
<tr>
<td></td>
<td>Max: 0.3110</td>
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</tr>
<tr>
<td></td>
<td>SD: 0.0590</td>
<td></td>
</tr>
</tbody>
</table>
4.3.1. Hypothesis 1 Methods

To test H1, which predicts that internalized norms of cooperation will lead *acequias* to adopt features which are more likely to promote equality and collective action, it must first be established that there is good evidence that norms of cooperation have been internalized. Therefore, before analyzing the data quantitatively, qualitative data obtained through direct observation, irrigation manager surveys, and key stakeholder interviews are given to contextualize the quantitative results that follow.

For quantitative analysis, 13 features which ought to engender higher levels of cooperation were identified (Table 4.4). Each irrigation system was then assessed for the number of features they exhibited in 2013. Features which should generate equality, increase mutual accountability, benefit the common resource or infrastructure, increase reliance on the common resource or infrastructure, or generate or allow more equal access to public goods (e.g. trust, institutions, food security, ecosystem services) should promote cooperation (Poteete et al., 2010) and therefore serve as evidence of cooperative norms.

Table 4.4. 13 features that ought to engender collective action on an irrigation system. The presence of these features is used to assess the relative preponderance of cooperative norms as opposed to competitive norms. The percentage of each ditch type which possess the trait in question is given.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Likely Effect on Equality, the Commons, Reliance on the Commons, and Public Goods</th>
<th>Percentage Distribution of Feature</th>
</tr>
</thead>
</table>
| No High Capacity Groundwater Wells | Compared to common property surface supplies, private groundwater wells lower the water table, diminishing others’ access to seeps, springs, subirrigation, and streamflow while harming the commons and diminishing ecosystem services. The | Taos *Acequias*: 100.0  
Costilla *Acequias*: 83.3  
Conejos *Acequias*: 45.4  
Anglo Systems: 13.0 |
alternative supply reduces reliance on the common property surface infrastructure.

| NO SPRINKLERS | Compared to flood irrigation, sprinkler irrigation reduces or eliminates groundwater recharge and tailwater, diminishing others' access to seeps, springs, subirrigation, return flows, and streamflow while harming the commons and diminishing ecosystem services. | Taos Acequias: 88.9  
Costilla Acequias: 75.0  
Conejos Acequias: 50.0  
Anglo Systems: 17.4 |
| PER CAPITA VOTING | Per capita voting ("one land owner, one vote") equalizes political influence among irrigators, making it more likely that a greater proportion of the commons will be maintained, and a larger proportion of irrigators will participate in decision-making, increasing the perception that decisions are fair. | Taos Acequias: 94.4  
Costilla Acequias: 91.7  
Conejos Acequias: 88.9  
Anglo Systems: 52.2 |
| LABOR REQUIRED FOR WATER ACCESS | Requiring labor for water access equalizes the contribution of each irrigator to the maintenance of the commons, ensures ongoing maintenance of common irrigation infrastructure, and increases visibility of and accountability for maintenance. | Taos Acequias: 88.9  
Costilla Acequias: 66.7  
Conejos Acequias: 11.1  
Anglo Systems: 13.0 |
| ROTATIONAL WATER DELIVERY | Rotation ensures that tail-enders receive water, equalizing water delivery. Further, because each irrigator is owed water, the maintenance of the irrigation system necessary to deliver the water is more likely; irrigators receiving water are more likely to act collectively than those who do not. | Taos Acequias: 88.9  
Costilla Acequias: 83.3  
Conejos Acequias: 61.1  
Anglo Systems: 21.7 |
| WATER NOT ALLOCATED BY PRIVATE RIGHTS | Allocating water to users based on the flexible needs of their land, crops, and family, as opposed to relatively inflexible private rights, should increase equality of water allocations. Being able to negotiate water allocations in times of need ought to improve irrigators' willingness to contribute to maintenance and comply with rules. | Taos Acequias: 94.4  
Costilla Acequias: 83.3  
Conejos Acequias: 27.8  
Anglo Systems: 4.3 |
| CHANGING WATER ALLOCATIONS IN SCARCITY | In shortage, irrigation systems which change water allocations between irrigators ought to promote more equality and a sense of mutual obligation and fairness. | Taos Acequias: 94.4  
Costilla Acequias: 75.0  
Conejos Acequias: 66.7  
Anglo Systems: 78.3 |
| MONITORING AGENT PRESENT | Appointing a monitoring agent ought to prevent over-extraction from the commons, assure irrigators that rules are applied equally, and assure irrigators that rules are being followed, increasing trust. | Taos Acequias: 100.0  
Costilla Acequias: 66.7  
Conejos Acequias: 55.6  
Anglo Systems: 65.2 |
| ANNUAL MEETING | An annual meeting gives every irrigator a chance to have concerns addressed, promotes infrastructure maintenance and information sharing, and generates trust through face to face communication. | Taos Acequias: 100.0  
Costilla Acequias: 66.7  
Conejos Acequias: 66.7  
Anglo Systems: 82.6 |
| LONG LOTS PRESENT | The presence of long lots, a uniquely Hispanic form of land tenure in the study area, ensures that each irrigator has access to a wide range of soil types and ecosystem services. Long lots also direct tailwater and return flows directly into the surface water supply for reuse. | Taos Acequias: 100.0  
Costilla Acequias: 33.3  
Conejos Acequias: 0.0  
Anglo Systems: 0.0 |
| Vegetable Gardens Present | Vegetable gardens indicate that the irrigation system is directly feeding its users, increasing their reliance on the commons and the incentive to maintain irrigation infrastructure while improving local food security. | Taos Acequias: 88.9  
Costilla Acequias: 16.7  
Conejos Acequias: 0.0  
Anglo Systems: 0.0 |
|----------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Ongoing Inter-System Sharing Arrangements | Ongoing arrangements to share water with other systems ought to promote a sense of mutual obligation. Sharing arrangements also connect systems to otherwise less important areas of the watershed, increasing the need to maintain the commons in those places. | Taos Acequias: 55.6  
Costilla Acequias: 16.7  
Conejos Acequias: 5.6  
Anglo Systems: 13.0 |
| Bylaws Present | Bylaws are an institutional public good and create a common reference of the rules for all, equalizing power between irrigators in a dispute and promoting compliance with the rules. | Taos Acequias: 100.0  
Costilla Acequias: 33.3  
Conejos Acequias: 55.6  
Anglo Systems: 69.6 |

First, Hierarchical Cluster Analysis (HCA) using Euclidean distance measures and complete linkages was run to determine if cultural and geographic clusters (i.e. ditch types) emerge from the distribution of the 13 features from Table 4.4. Principal Components Analysis (PCA) was also used to further corroborate and visualize these relationships. This allows the analytical process to generate groupings endogenously rather than impose the groupings on the data.

Second, cultural and geographic groupings based on historical settlement patterns and contemporary law are imposed on the data. The distribution of the 13 features (Table 4.4) is described and assessed for significance using pairwise regressions across the four geographic and cultural groups: acequias from Taos, Costilla, and Conejos Counties, and Anglo systems.

Third, it could be argued that these features (Table 4.4) exist on an irrigation system for reasons pertaining geographic, economic, or demographic factors rather than norms. To test whether the number of features differs between Taos, Costilla, and Conejos acequias and Anglo systems while accounting for other important
factors, a Poisson regression was run using the number of features from Table 4 as the dependent variable (DV). The following control variables were included (Equation 4.1): 1) Days of normal water availability (WATNORM – natural logarithm transformed to better fit the assumption of normality); 2) Percent hydric soils (PERHYD); 3) Irrigation system acreage (ACRES – natural logarithm transformed to better fit the assumption of normality); 4) Percent Hispanic population (PERHISP); 5) Percentage renters (PERRENT); 6) Average farm acreage (AVEFARMSIZE); 7) Percent population unavailable for labor (i.e. dependency ratio, those aged under 10 and 65 or over) (DEPRAT). The last five variables serve as proxies for wealth. Larger irrigation systems, all else equal, have a larger base of capital and labor to draw upon. Furthermore, Hispanics in this region tend to be less materially wealthy, as do renters and those with smaller farms. Finally, a higher dependency ratio implies lower wage-earning potential, less available labor, and greater expenditures on dependents. An alternative specification was also run, where Costilla acequias and Taos acequias were binned together as a single covariate.

**Equation 4.1.** Predicting institutional and technological features.

\[ y_i = \beta_0 + \beta_1 CONEOS_i + \beta_2 COSTILLA_i + \beta_3 TAOS_i + \beta_4 AVEFARMSIZE_i + \beta_5 \log(ACRES)_i \]

\[ + \beta_6 \log(WATNORM)_i + \beta_7 PERHYD_i + \beta_8 \log(DEPRAT)_i + \beta_9 \log(AVEFARMSIZE)_i \]

\[ + \beta_10 \log(ACRES)_i + \varepsilon_i \]
Fourth, to test whether the presence of each individual feature could be attributed to the presence of cooperative norms, Logit regressions were run following Equation 4.1 with each of the features in Table 4.4 as a dichotomous DV.

4.3.2. H1 Results: Features Are Significantly Associated with Norms

4.3.2.1. Qualitative Analysis of H1: Distinct Norms Have Been Internalized

There is qualitative evidence that the internalized norms of Hispanic and Anglo irrigators tend toward cooperation and competition, respectively. In addition to the historical evidence presented above, direct observation, open ended survey questions, and key stakeholder interviews detected a greater emphasis on cooperation and community integrity among acequias and a greater emphasis on competitive behaviors and individual economic performance among Anglo systems.

These trends are especially apparent in the social enforcement of water rights. With regards to water use violations, Anglos noted that “everyone borrows water,” “there’s always someone up to something,” and “it’s just part of the system.” Competitive norms among Anglos stipulating private pro-rata shares of water within an irrigation system tended to be enforced through graduated sanctions such as verbal confrontation, social shaming, locking of private headgates, and revocation of pro-rata shares (the latter two being performed by the Ditch Rider or board of the irrigation system). Rarely, the power of law was invoked, such as calling the Sherriff to register a formal complaint or engaging in a lawsuit. Rather, if the above social mechanisms failed, more extreme social measures were taken,
such as: pouring herbicide in the ditch leading to an offender’s field, shocking crops; clogging the ditch with debris and trash, requiring tedious labor to remove; and shooting cows, inflicting a direct economic loss while also threatening violence. These enforcement mechanisms appeared to be somewhat effective deterrents to the temptation to take more water than owed. As one Ditch Rider said, “[You] Don’t want to be on [the] bad side of neighbor and get shot.” Acequias also experienced violations of the norms around the negotiated allocations of water, but water was described as being taken in “neighborly amounts” with the recognition that the farmers “have to live together.” While there were certainly instances of frequent violations by the “usual suspects” and at least one sibling feud, tensions tended to resolve themselves after a conversation with the mayordomo, social shaming at the annual meeting, a fine of $50-100 per violation, or having water cut off for a period of time, usually one turn in the rotation. While one mayordomo acknowledged that, “We have our arguments and discussions,” these disputes – “often miscommunication,” as could be expected in a system based around negotiation – rarely escalated to vigilante sabotage of infrastructure (e.g. “tear up gear,” as reported by one Anglo), and no contemporary threats of violence were reported.

The interaction of the norms of Anglo irrigators and the norms of Hispanic irrigators is also instructive as to whether divergent norms have been internalized. A mayordomo in Conejos County indicated that once Anglos bought land on his relatively small acequia, cooperation broke down. He said the Anglos believed the water right on their deed reflected an absolute amount of water that was their
private property to which they were fully entitled under any circumstances, and that they had no responsibilities to others on the system. As a result, ditch maintenance costs fell entirely to the *mayordomo* and infrastructure declined accordingly. Water sharing also ceased to occur. The Anglos did not come to meetings, physically withheld bylaws and other necessary paperwork, and refused to respond to letters requesting cooperation. They also called upon the state to intervene and do away with a cornerstone of *acequia* water governance: rotational water delivery, which ensures every farmer receives a share of water in turns. No social pressure had altered these circumstances, and the *mayordomo* lamented that he was not wealthy enough to pursue legal actions to force even their minimum legally required responsibilities to ditch maintenance.

4.3.2.2. Quantitative Analysis of H1: Distinct Norms Are Associated with Different Features of Self-Governing Irrigation Systems

HCA corroborates the geographic and cultural groupings expected from theory and history (Table 4.1) and illustrates the cultural relationships between individual irrigation systems (Figure 4.1). In Figure 4.2, Taos *acequias* present as a distinct cluster and Costilla *acequias* are most closely related to those in Taos. Conejos *acequias* fall along a continuum ranging from being more closely related to Costilla *acequias* to being more closely related to Anglo systems, which themselves are relatively distinct. Within the largely Anglo cluster, a sub-cluster emerges that is comprised entirely of *acequias*.
**Figure 4.2.** Relatedness between irrigation systems based on the features in Table 4.4. Taos *acequias* all fall within the same cluster, with some Costilla *acequias* interspersed. A small cluster of Costilla *acequias* also emerges, and all but two of the remaining Costilla *acequias* fall within a third cluster which is two thirds Hispanic. Anglo systems and Conejos *acequias* make up the vast majority of the final cluster, which has a sub-cluster comprised entirely of *acequias*.

PCA (Figure 4.3) supports the distinctions between the clusters, showing more clearly than Figure 4.2 that most Anglo systems are different from most *acequias*, and that Taos *acequias* are also quite distinct. The same general trends are also observed, where Costilla acequias are more closely related to Taos acequias than are Conejos *acequias*, and that Conejos *acequias* comingle with Anglo systems.
Figure 4.3. PCA shows the relatedness between irrigation systems based on the features in Table 4.4. Taos remains apart from the other systems, with Costilla acequias being largely distinct from Anglo systems. Conejos acequias range from being more closely aligned with Costilla acequias to nearly identical to Anglo systems.

Figure 4.4 imposes structure on the data and is purely descriptive. It shows that acequias have higher frequencies of the features identified in Table 4.4. As acequias became more exposed to Anglo influence, the average occurrence of these features falls from Taos, to Costilla, to Conejos. Pairwise Poisson regressions with a suppressed intercept reveal that all ditch types are significantly different (p < 0.01) from each other with respect to the count of the 13 features from Table 4.4.
Figure 4.4. Geographic and cultural distribution of cooperation-engendering features from Table 4.4. The differences in this figure between all ditch types are significant to $p < 0.01$.

Independent of the effects of other important variables included in Equation 4.1, Poisson regressions (Appendix C Table C.2 and C.3) reveal acequias from Costilla ($p < 0.05$) and Taos ($p < 0.01$) are significantly more likely to possess features from Table 4.4 as compared to Anglo systems. However, Conejos acequias show no significant difference from Anglo systems. These results are consistent whether or not Costilla and Taos acequias are grouped together. Using different
reference groups reveals that Taos *acequias* are significantly different (p < 0.01) from all other ditch types, as are Costilla *acequias* (p < 0.05). No other variables in Equation 1 significantly predict the DV.

Logit regressions also support the hypothesis that norms of cooperation have been internalized on *acequia* systems (Appendix C Table C.4 and C.5), despite features of *acequias* in Conejos county having converged to some extent with Anglo systems in response to legal and market pressure. Although insignificant for some features, the Logits reveal that the most consistent association with the adoption of any of the 13 features is the irrigation system’s cultural origin and subsequent history. The only other variable included in Equation 1 that significantly predicts more than two DVs is the acreage of the irrigation system. These results are also consistent whether or not Costilla and Taos *acequias* are grouped together.

The weight of the qualitative and quantitative evidence suggests that relatively more cooperative norms have been internalized on *acequias* while relatively more competitive norms have been internalized on Anglo systems, and that this has manifested in irrigation system features congruent with these norms.

4.3.3. H2, H3, and H4 Methods

Having established good evidence that cooperative norms have been internalized on *acequias* as compared to Anglo systems which are more competitive, regressions were performed to test H2, H3, and H4 (Equation 4.2). Equation 4.2 uses variables deemed important for predicting the DVs in the literature, having a
strong effect in preliminary analysis (pairwise regressions, ANOVAs), and lacking multi-collinearity (variance inflation factors ≤ 5.0). New variables include: US state of the irrigation system (STATENM), deviation from days of normal water availability in the 2012 drought as a proxy for drought sensitivity (NORM2012), sprinkler presence (SPRINK), adoption of bylaws (BYLAW), changing water allocations in water scarcity (SHRSRC), and rotational water delivery in water scarcity (ROTSRC).

**Equation 4.2.** Predicting irrigation outcomes.

\[
y_i = \beta_0 + \beta_1 COSTILLA&TAOS_i + \beta_2 CONEJOS_i + \beta_3 MDDR_i + \beta_4 COSTILLA&TAOS_i * MDDR_i + \beta_5 CONEJOS_i * MDDR_i + \beta_6 ROTSRC_i + \beta_7 SHRSRC_i + \beta_8 PERHISP_i + \beta_9 DEPRAT_i + \beta_{10} SPRINK_i + \beta_{11} PERRENT_i + \beta_{12} PERHYD_i + \beta_{13} BYLAW_i + \beta_{14} NORM2012_i + \beta_{15} log (ACRES)_i + \beta_{16} STATENM_i + \epsilon_i
\]

Equation 4.2 includes an interaction between an irrigation system’s status as an *acequia* from Conejos (CONEJOS) and an *acequia* from Taos or Costilla (COSTILLA&TAOS) with the presence of a monitoring agent (MDDR). Anglo systems are the reference level. For *acequias* in Costilla and Taos, all but three monitoring agents administer water according to traditional common property norms, as do all *acequias* there without monitors. All Anglo system monitors allocate water based on private rights, and only one Anglo system without a monitoring agent does not. By contrast, rules and norms are in conflict within Conejos *acequias* due in part to state law; all but one monitoring agent among them enforces private rights to water, while only half of the systems without monitors
enforce private rights. Bearing in mind the qualitative data introduced above, it is reasonable to believe that traditional common property norms still prevail among many irrigators on systems that administer water based on private rights.

The first regression, a Logit, tests whether or not water use violations occur once per year or more as a dichotomous DV. OLS regression was then used to predict the mean NDVI for an irrigation system, a proxy for overall crop production ranging from zero to one collected by remote sensing and retrieved from GoogleEarth Engine. Mean NDVI in the month of July in the years 2011-2014 was modeled because July has peak crop growth and lacks cloud obstruction. 2011-2014 were used because the survey was conducted in 2013 and because all years were drought years to some degree. Mean July NDVI was scaled (mean-centered, divided by standard deviation) to ease interpretation of the results. OLS is also used to test H2, H3, and H4 to predict the mean spatial standard deviation of NDVI in July of each year. This was also scaled for ease of interpretation.

Several robustness checks were done. Regressions were run with Taos removed to check if results were sensitive to the inclusion of data from New Mexico. To account for spatial auto-correlation, spatial error models were also run. Finally, regressions were run with all acequias aggregated together and compared to Anglo systems (Appendix C Table C.7, Figures C.1-C.3), bearing in mind that tests of H3 and H4 were not possible when aggregating all acequias and that this aggregation would bias results and increase standard errors for acequias due to meaningful
differences between Conejos *acequias* and the others. These robustness checks all agree with the results presented below.

### 4.3.4. H2, H3, and H4 Results: Norms Moderate the Influence of a Monitoring Agent

Regressions reveal significant interactions between the presence of a monitoring agent and norms (Appendix C Table C.6). The regressions show that aside from cultural factors, only the irrigated area of the system significantly (p < 0.05) increases water use violations. Irrigated area also significantly (p < 0.01) decreases mean NDVI and increases the standard deviation of NDVI. The use of sprinklers and higher water availability in drought also significantly (p < 0.01) increase mean NDVI. Finally, percentage of renters and percent Hispanic are weakly significantly (p < 0.1) associated with higher standard deviation of NDVI.

Figures 4.5-4.7 make the results clearer in relation to the hypotheses. Figure 4 supports H2, H3, and H4. The predicted probability of water misuse is higher with a monitoring agent than without on Conejos *acequias*. A plausible interpretation is that irrigators on Conejos *acequias*, where water is being allocated by rules that are in tension with norms, may be flouting what they view as illegitimate rules. In contrast, a monitoring agent is associated with essentially identical levels of water misuse among *acequias* from Costilla and Taos, suggesting no crowding-out, and lower water misuse among Anglo systems, suggesting effective deterrence.
**Figure 4.5.** Predicted probability of water misuse occurring once per year or more due to an interaction between a monitoring agent and different ditch types. 95% confidence intervals.

![Norms Moderate Effect of Monitoring on Probability of Rule Violation Frequency](image)

Figure 4.6 and Figure 4.7 should be considered together, since both assess different features of crop production which may be interdependent. That is, system-wide average crop production may be driven partially by differences in the equality of crop production across the system (Smith, 2014). Results for Anglo systems show that a monitoring agent is associated with higher average crop production, supporting H2, and no difference in the equality of crop production, contradicting H2. A parsimonious interpretation is that monitoring agents on Anglo systems ensure water is delivered in line with law and norms which emphasize individual
rights to water and economic efficiency, and that this allows irrigators to maximize crop growth on the most productive lands. The lack of change in crop production equality combined with greater average production with a monitoring agent suggests that without a monitoring agent some water is wasted, neither increasing equality nor average crop production.

**Figure 4.6.** Predicted average NDVI over the study period due to an interaction between a monitoring agent and different ditch types. 95% confidence intervals.
Figure 4.7. Predicted average spatial standard deviation of NDVI over the study period due to an interaction between a monitoring agent and different ditch types. 95% confidence intervals.

**Norms Moderate Effect of Monitoring Agent on Standard Deviation of NDVI (2011-2014)**

Results for Taos and Costilla *acequias* show lower average crop production and lower inequality with a monitoring agent than without, supporting H3. Based in and congruent with cooperative norms, the monitoring agent enforces negotiations around water allocation and delivery which result in these *acequias* trading higher average crop production for more equal crop production. In contrast to Anglo systems, water not used to increase average production is not wasted, it is redirected towards greater equality. Where a monitoring agent is absent, the negotiated delivery and allocation system used by *acequias* may be relatively more
influenced by competition due a lack of enforcement, leading to higher average crop production but greater inequality. After all, while norms may be more cooperative on average on acequías, selfish temptation is still present. Systems without a monitoring agent to enforce greater equality would be more likely to see that temptation realized, and thus produce lower equality and, conversely, higher average crop production. Notably, that competition does not result in increased water use violations, suggesting the negotiated water allocations are the source of the increased inequality.

Finally, Conejos acequías have worse average production when a monitoring agent is present, supporting H4, with no differences in crop production equality, contradicting H4. Like the increased water use violations under a monitoring agent observed in these acequías, this loss of production may be due to the discord resulting from allocating water along private rights deemed illegitimate by a sufficient percentage of irrigators. There is no evidence of a tradeoff between average production and the equality of production on Conejos acequías. This suggests that monitoring agents of Conejos acequías are simply unable to effectively enforce private water rights, leading to wasted water.

The results from tests of H2, H3, and H4 for water use violations, average crop production, and equality of crop production are summarized in Table 4.5.


Table 4.5. Results with respect to norms, water rights, and monitoring. The sign in parenthesis indicates the direction of differences observed between systems with a monitoring agent and no agent when compared to the same Ditch Type.

<table>
<thead>
<tr>
<th>Ditch Type</th>
<th>Norms</th>
<th>Water Rights</th>
<th>Monitoring Agent</th>
<th>Water Use Violations</th>
<th>Average Crop Production</th>
<th>Equality of Crop Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anglo systems</td>
<td>Competitive</td>
<td>Pro-Rata Shares</td>
<td>Yes</td>
<td>(-)</td>
<td>(+)</td>
<td>(=)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>(+)</td>
<td>(-)</td>
<td>(=)</td>
</tr>
<tr>
<td>Conejos acequias</td>
<td>Cooperative</td>
<td>Pro-Rata Shares</td>
<td>Yes</td>
<td>(+)</td>
<td>(-)</td>
<td>(=)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>(-)</td>
<td>(+)</td>
<td>(=)</td>
</tr>
<tr>
<td>Costilla &amp; Taos acequias</td>
<td>Cooperative</td>
<td>Need and Prior Use</td>
<td>Yes</td>
<td>(=)</td>
<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>(=)</td>
<td>(+)</td>
<td>(-)</td>
</tr>
</tbody>
</table>

4.4. Discussion: The Importance and Relevance of Norms in Context

With regards to the evolution of norms, the differences between the Anglo and Hispanic irrigation models (typified by Taos acequias) provide evidence that selection pressures generated by legal, economic, technological, and ecological context can drive the internalization of norms that improve group and individual relative fitness (Richerson & Boyd, 2001; Richerson et al., 2002; Waring et al., 2017; Wilson et al., 2013). The geographic gradient of features that ought to engender cooperation which has emerged over the past 150 years is further evidence that irrigating communities adapt their physical and institutional features to local contexts (van der Kooij et al., 2015). Evidence suggests the convergence between some Colorado acequias and the Anglo model of irrigation is largely the consequence of state law, Anglo land owners, and globalized commodity markets providing pressure to alter ditch operations among acequias (Randhir, 2016). Absent legal protection similar to that afforded by New Mexican law, it may not be feasible for acequias to survive in Colorado without adaptations which fundamentally alter their identity. Therefore, a closer look at the results is warranted.
The features in this study which already show no significant differences in their distribution, particularly in Colorado, are largely collective choice and constitutional rules (Ostrom, 2005), such as the presence of bylaws, an annual meeting, per capita voting, and labor requirements for membership. It appears that these features are less influenced by differences in norms and are driven more by the selection pressures on all irrigation systems in Colorado and other contextual features. In contrast, the features which were most distinct between *acequias* and Anglo systems were operational rules dealing directly with irrigation: the ways in which water was acquired (*repartimiento v.* Prior Appropriation, groundwater wells present or not), moved through the system (rotational delivery or not, privately allocated or not), and applied to the land (flooding v. sprinklers). This implies that even if new technologies such as wells and sprinklers are available that generate improved economic efficiencies for individuals, irrigation systems may not adopt them if they would disrupt pro-social norms that provide community cohesion. Despite the legal ability to interfere, it would be politically challenging, especially given the recent *acequia* recognition law, for Colorado to do away with rotational delivery or force the adoption of wells, sprinklers, and pro-rata shares on recognized *acequias*. However, in a changing climate with potentially higher commodity prices, there will be even greater pressure on individuals to adopt more selfish technologies and demand changes to water allocation rules that maximize individual profit. Without adequate reinforcement of norms or benefits drawn from the community, these operational rules could tip towards the Anglo model, which is well adapted to
the market and handles shortages largely through technology. That said, there is evidence that *acequias* retain traditional coping mechanisms based in shared sacrifice (Hicks & Peña, 2003) that could avoid this conclusion.

The differences in irrigation performance identified in this study are instructive in efforts to understand how climate change might impact irrigation systems. It does not appear that a monitoring agent crowds-out cooperative norms on *acequias* in Taos and Costilla, as some literature suggests is possible (Kinzig et al., 2013; Rode et al., 2015), but rather may be crowding-in cooperative norms (Rode et al., 2015) and generating more equal crop production at the expense of average crop production (Smith, 2014). It also appears that social sanctioning is sufficient to achieve rule compliance where norms are cooperative (Falk et al., 2012), but not to achieve more equal crop growth. Therefore, it appears that for *acequias* that have not been dramatically disrupted by Anglo institutions, a *mayordomo* may be very important for reinforcing cooperative norms and ensuring shared benefits of self-governance as aridity worsens. However, where cooperative norms are in conflict with private rights to water among Conejos *acequias*, a monitoring agent enforcing private rights is associated with an increase in water use violations and lower average crop production, similar to previous findings where norms and rules conflicted (Kamran & Shivakoti, 2013; Vollan et al., 2013; Hoogesteger, 2015). In this instance, a monitoring agent could be an impediment to successful adaptation to climate change and may even be a catalyst for changes to *acequias* which deviate from cooperative norms. It appears there is a tremendously difficult challenge
ahead for Conejos acequias, where norms and rules will need to be adjusted to accommodate each other, local and global climate change, and impending groundwater regulations (Smith et al., 2017).

4.5. Chapter Conclusion

This study has implications for CPR governance in both developed and developing countries, in particular governance of irrigation systems under water stress (Skjølvold, 2010). It also generates new questions about the role of norms in an increasingly integrated economy where CPR use and governance are local but products of the CPR are sold in a global market (Randhir, 2016). Results demonstrate that self-governing irrigation systems with internalized norms of cooperation tend to implement rules and adopt technologies which aim to sustain the commons, provide public goods, and promote equality between irrigators, all of which improve resilience of the global food supply to climate change. However, they may be less competitive in a global market due to lower average crop production. Furthermore, the role of norms in shaping the features of self-governing irrigation systems interacts with market and legal context. Enforcing rules which are congruent with community norms generate better rule compliance and performance, but enforcing rules that are incongruent with norms leads to worse outcomes.

In light of these results, it may be warranted to legally recognize or otherwise support self-governing CPR regimes which, following investigation, meet the normative goals of the user community in terms of resource production (e.g. average
crop growth) and social cohesion (e.g. water use violations, crop production equality) (Hoogesteger, 2015; Skjølsvold, 2010). In an era of climate change, interventions need to be carefully coordinated with the target community in order to diagnose specific problems that can be solved while maintaining adaptive norms (Meinzen-Dick, 2014). State law (e.g. Colorado’s acequia recognition law, New Mexican water law) and non-state actors (e.g. The Acequia Assistance Project of CU Boulder Law School) could play a supportive rather than prescriptive role in assisting self-governing irrigation systems to achieve climate change adaptation.

This study adds weight to the growing body of work giving greater attention to cultural context when analyzing user-governed CPR regimes and climate change resilience, and further illustrates the compatibility of MLS Theory with other prevailing theories in CPR research. Future work might address questions of long-term resilience to climate change as it relates to tradeoffs between market integration and subsistence modes of production, as well as how competitive norms interface with enforced common property rights.
CHAPTER 5

CONCLUSION

5.1. Overview of Preceeding Chapters

This dissertation assessed the role of context in shaping the influence of rules on the outcomes of self-governing irrigation systems in the URGB. The investigation responds to a number of applied concerns stemming from the impacts of climate change on water supplies for irrigation and food security, as well as a number of theoretical questions about the relative contribution of institutions to sustainable resource management. The empirical chapters analyzed how rules interact with context – specifically, biophysical context, other rules, and cultural norms – to influence irrigation performance in self-governing irrigation systems under climate change. Except for a few instances, these interactions were significantly influential for outcomes important for climate change adaptation. These interactions with context emphasize that policy panaceas to resource management problems are unlikely to be universally successful, an important theme for scholars and practitioners alike.

The empirical investigations were organized using the IAD framework, CPR theory, and to a lesser extent MLS theory. Conceptually, by designing these studies of self-governing irrigation systems in line with the broader CPR literature, the
results of this dissertation are potentially portable to other CPRs such as forests, rangelands, and fisheries. The rules and contextual factors studied were intentionally selected to be general enough to apply to other CPRs but specific enough to be practically meaningful to irrigators in the URGB and elsewhere. By studying self-governing irrigation systems in the URGB, the study exploited contemporary signals of climate change, historically dependent cultural differences, and a diverse population of self-governing irrigation systems to test hypotheses that would be difficult to test in a more homogenous and climatically stable setting.

Results from the first empirical chapter (Chapter 2) demonstrated that *de facto* access rights to a CPR are highly influential alone and in interaction with biophysical context for determining CPR outcomes. From an initial dataset of 639 self-governing irrigation systems in Colorado’s URGB, the chapter employed genetic matching to reduce this to 402 readily comparable systems. Data on these systems were compiled for a 32-year period from 1984 to 2015, a period that saw snowpack decline and temperature increase in line with expectations under climate change. Regression methods then assessed several hypotheses related to the role of water rights and biophysical variables on the duration of water diversion, the volume of water diversion, and the area irrigated. An important contribution of this chapter was to place water rights in context, arguing that the influence of water rights is significantly moderated by factors such as the number of upstream diverters, whether the irrigation system diverts from a tributary stream or mainstem river, the watershed area, and accumulated snowpack. Other contextual factors, such as
cultural differences and an interstate compact, did not produce significant interactions with water rights, but there are good reasons to believe that in some cases these factors may significantly interact. Practically, this chapter shows that water rights reform could be a powerful lever of adaptation to climate change in the American West given the pervasive role of water rights in irrigation outcomes.

The second empirical chapter (Chapter 3) showed that user-originated rules significantly interact to produce CPR outcomes, and that outcomes under the same configuration of rules can differ depending on other biophysical variables such as resource availability and location of the CPR user. This chapter made use of a semi-random stratified sample of 60 self-governing irrigation systems in Colorado’s URGB conducted in 2013 and spatial data on 6711 individual irrigated fields nested within the jurisdictional boundaries of those systems. It studied a four-year drought from 2011-2014 using regression methods to assess three outcomes: whether a field was irrigated or fallowed, the percentage of the total area of a field that was irrigated, and the crop growth of that field as measured by NDVI. The chapter hypothesized and corroborated that two user-originated rules, rotational delivery and flexible water allocations, interacted to generate varying levels of irrigation performance. The chapter also hypothesized that different combinations of those rules produced different outcomes depending on two other factors: how far a field was from the point of diversion and how much water was diverted. The major contribution of this chapter was the finding that outcomes for a given field under a given rule depend on physical water availability, the location of the field on the
canal system, and at least one other rule. Although not investigated, it is likely that other rules and contextual factors further condition the influence of a focal rule. Of particular relevance to climate change adaptation, the equality of outcomes between head-enders and tail-enders is sensitive to rule configurations and water availability. Due to the role of perceptions of fairness in shaping irrigators willingness to act collectively and the role of collective action in adapting to climate change, this chapter’s results imply that configurations of rules that produce highly unequal outcomes may inhibit adaptation whereas configurations that produce greater equality may catalyze it.

Finally, the last empirical chapter (Chatper 4) found that cultural norms are significantly associated with an array of technological and institutional choices of CPR users and also significantly moderate the influence of rules on CPR outcomes. The chapter expanded the semi-random stratified sample to 78 self-governing irrigation systems in the URGB of Colorado and New Mexico. It exploited the 350-year history of two culturally distinct colonizing European groups, Hispanics and Anglos, and a contemporary four-year period of drought from 2011-2014 to test hypotheses informed by MLS and CPR theories. There are two major contributions of this chapter. The first is theoretical: predictions made using MLS theory about the technological and institutional features of irrigation systems were validated, adding legitimacy to the use of MLS theory in CPR research. Specifically, by assessing historical factors relevant for the evolution of cooperation, such as whether crops were grown primarily for subsistence or for markets, the relative
ease of monopolizing resources and generating intra-group heirarchies, and the intensity of competition with other groups, this chapter predicted that Hispanic irrigation systems would exhibit relatively more characteristics congruent with cooperative norms than Anglo systems. The second contribution is more practical: the chapter adds empirical evidence to the argument that cultural norms are important factors to consider when contemplating policy interventions. As the climate changes, the co-evolutionary relationship between norms, rules, and technology explored in this chapter implies that changes to rules or technologies that are incongruent with existing norms may not promote the intended behavior changes in the short or long term, potentially frustrating adaptation.

5.2. Opportunities for Future Research

A shortcoming of this dissertation is that it does not directly address climate change adaptation, only irrigation outcomes in water shortage. Although it may be a valid assumption that adaptation to contemporary climate variability will serve as adaptation to climate change in the short or medium-term, in the long-term this is unlikely to be the case (Dilling et al., 2015; Kates et al., 2012). Future research should go beyond specific adaptations to shortage and investigate the institutional mechanisms and contexts that enable adaptations to emerge through collective action (Arunrat et al., 2017; Chhetri et al., 2012), such as poly-centric governance (Ostrom, 2010; Pahl-Wostl et al., 2012). This research should include more than just surface and groundwater supplies to include adaptability to ecological, economic,
and other disturbances to forests, rangelands, and fisheries. Future work should also interrogate energy and mineral resources and farmlands (and their soils), essential resources for future climate change adaptation measures and sustainability. Ostrom’s (1990) design principles for long-lived CPR regimes should be a starting point because they were identified and verified by studying many CPR regimes across cultures and nations which have survived via successful adaptation over time, implicitly through an evolutionary process of selection (Cox et al., 2010; Schoon & Cox, 2018), and have been shown to be analogous to important parameters of successful collective action among groups of various kinds, not just those managing CPRs (Wilson et al., 2013). Collective choice and constitutional rules, as opposed to operational rules, as well as more developed hypotheses of how polycentricity acts to confer adaptability, will be of growing importance as the climate changes and the global economy becomes more integrated (Andersson & Ostrom, 2008; Laube et al., 2012; Morrison et al., 2017; Pike et al., 2010). Given the uncertainties of climate change and pace at which it may unfold, adaptability may be more important for sustaining CPR and other resource regimes over time than any specific adaptations (Barnett et al., 2015; Kates et al., 2012).

Because adaptation will require collective action, and collective action is made more likely when the actors involved view the arrangements as fair (Ostrom, 2005), distributional effects of institutions will be important for climate change adaptation. In each of the three empirical chapters, institutions were shown to produce more or less equal outcomes depending on a wide array of factors, such as
water rights, geographic location, physical water availability, user-originated rules, technological choices, monitoring, and cultural norms. This implies that an even wider array of factors can influence inequality within irrigation systems, as some research has already investigated (Manero, 2017; Mollinga, 2014). However, more work remains to be done on linking institutions, equality, and propensity for collective action. More work also needs to be done to understand under what conditions those made better off by an institutional arrangement are willing to sacrifice some or all of their advantage so that those made worse off can avoid the worst consequences of water shortage and other climate change impacts.

Finally, more specific to the research conducted in this dissertation, there is room to expand the work into other basins in Colorado, to repeat the surveys from this dissertation to generate a time series of institutional change, and to incorporate groundwater governance more directly. Conducting similar research in different legal, hydrologic, political, and economic contexts would add to the body of knowledge generated in this dissertation and provide novel insights into the transferability of results. Furthermore, a time series of institutional change would be a valuable basis for investigations into the reasons for institutional change as well as the results of it. Although groundwater access was considered in this dissertation, the SLV is undergoing dramatic groundwater governance changes (Cody et al., 2015; Smith et al., 2017), and the rest of the American West and other arid regions of the world are facing growing groundwater stress (Richey et al., 2015). From a poly-centric perspective, it is reasonable to suspect that surface water
irrigation systems behave differently when also under some form of groundwater governance, and conversely that groundwater governance regimes would experience different outcomes and processes depending on the institutional arrangements in place for surface water governance. The Arkansas Basin and South Platte Basin in Colorado both offer unique cases in groundwater governance that can be readily compared to the SLV. And because the same data are available for surface water irrigation systems in all three basins, these are promising areas for future research.

5.3. Policy Implications

5.3.1. Water Rights Reform Is Possible, Will Be Facilitated by Climate Change

Taken as a whole, this dissertation produces a few fundamental policy implications. First, policy-makers should be careful not to upset important causal links to desired outcomes by ignoring context, assuming that changes to one part of the system can occur in isolation, or that changes will cause negligible impacts to other parts of the system. For an international example, in 1981 Chile codified a then-favored panacea in water resource management: privatization and free markets in water rights. This was an effort to create tradable water rights so that water would be allocated more efficiently based on prices (Budds, 2004); those who could produce more with a unit of water would pay more for it, ensuring that water went to its highest and best use. Despite the conceptual merits of this design, the intervention was not tailored appropriately to context. The market has tended towards monopolization and speculation, and has not produced the expected
productivity gains (Chikozho & Kunjinga, 2017; Boelens & Vos, 2012). Similar to PA, those with large and secure water allocations have little incentive to be efficient with its use. For the poorest subsistence farmers, the policy design has lead to disruptions of traditional management institutions in communal irrigation systems, leading to greater hardship, especially in scarcity and for those at the tail-end of irrigation systems (Boelens & Vos, 2012).

A similar lesson can be drawn from policies aimed at improving water use efficiency through technology subsidies and transfers. Although water use efficiency may improve at the scale of the farm or irrigation system, at larger scales such as whole catchments or basins the efficiency gains may result in worse ecological or economic outcomes (Batchelor et al., 2014; Pfeiffer & lin, 2014; Sears et al., 2018; Van Halsema & Vincent, 2012). The role of contextual factors in all three empirical chapters suggests that the influence of a given policy depends greatly on many factors, including monitoring and enforcement, geography, technology, and culture.

In light of this, while Chapter 2 suggests that water rights are a potential lever of climate change adaptation, and other studies suggest reform would result in more economically efficient and equitable outcomes than PA (He et al., 2012; Kenney, 2005), a wholesale undoing of the water rights regime in the American West is unlikely to be politically possible or socially or economically beneficial in the short to medium term. A fundamental change such as this would offend the deeply held norms of Anglo irrigators and devalue the billions of dollars of infrastructure
that has been built and on-farm investments that have been made assuming existing water law would persist.

That said, at the 2017 annual meeting of the Colorado Section of the American Water Resources Association, former Colorado Senator and Secretary of the Interior Ken Salazar stated that while PA is the law, there will need to be work on management and policies that can evolve around PA to meet future needs under climate change, such as population growth and environmental demands. Crucially, Salazar went on to argue that as people understand the full effects of climate change, PA will be made to accommodate it. This is a crucial point. Cody et al. (2015) argued that biophysical shocks to resource systems drive the most fundamental changes to those systems. This implies that as the supply of water decreases, people will be willing to make more and deeper changes to adapt. As Benjamin Franklin said, “When the well is dry, we know the worth of water.” It is likely, then, that as climate change impacts are more deeply felt, stakeholders will be more willing to negotiate governance alternatives, including changes to water rights.

Secretary Salazar’s former Deputy Secretary Mike Connor spoke at the same conference, and argued further that federal law and policy can also force stakeholders to the table, particularly through environmental laws such as the Clean Water Act, Endangered Species Act, and National Environmental Policy Act. Connor noted that states have strong powers and a leadership role in the realm of water rights, since the state level is where water rights are defined. In effect, two of the most powerful water management officials from the Obama Administration
argued for a poly-centric approach, where multiple centers of power devote their expertise to coordinating policy to generate desired outcomes.

To Connor’s point that water rights are a state concern, policy could alter what rights water rights actually confer. For example, as former Colorado State Supreme Court Justice and water law expert Gregory Hobbs Jr. has noted many times, “beneficial use” is the basis, the measure, and the limit of a water right under PA. Changes to what is considered a “beneficial use” and how that use is measured and valued could be powerful mechanisms to reform water rights. Water rights in Colorado have already changed in two important ways over the past 40 years. Water rights had traditionally been partially defined by a diversion of water from a natural body of water, yet this is an evolving concept which now allows for diversion to occur within the stream itself for recreational purposes. Colorado also has a legal framework for in-stream flows for environmental purposes, something not envisioned at statehood. Other states have innovated other mechanisms, such as the Public Trust Doctrine. In principle, these accommodations of contemporary values point to the possibility of water rights reform that also accommodates climate change without violating the Takings Clause of the US Constitution.

Even absent fundamental reforms to water rights, it is possible to imagine numerous pathways for water rights to be managed so that the least efficient and most ecologically damaging features of PA are mitigated given Colorado’s commitment to the Basin Roundtable process as the basis for statewide water planning, the ability to establish special districts and joint power authorities,
obligations under national and international treaties, and the contracting that can occur between water rights holders. Across the West, similar state planning processes and regional water management bodies exist. There are also examples of contractual negations of priority; in the early 1990s, facing groundwater overdraft and enticed by the potential of increased access to surface water, the various urban water utilities that serve the Las Vegas, NV area abandoned priority between themselves, opting for “common priority” to their collectively pooled water rights (Cody, 2011). A distinct but related approach has been taken by some acequias in the SLV, with those on Los Piños creek in Rio Grande County maintaining their individual rights but legally ignoring priority. Because they own all the water rights on the creek and the creek is fully consumed, no downstream users can claim injury. In effect, because PA confers private rights, private users can be persuaded through policies, norms, economics, and biophysical realities to make decisions that result in socially and ecologically beneficial outcomes without fundamental changes to PA.

5.3.2. Policy Should Promote Outcomes, Not Prescribe Mechanisms

The second policy implication of this dissertation that it may be warranted for policy-makers to be conditionally supportive of endogenous initiatives to improve outcomes and adaptation processes that arise from CPR users, provided these initiatives are in line with broader policy goals at larger spatial and temporal scales. Local actors tend to have more “knowledge of the particular circumstances of time and place” (Hayek, 1945: 521), and therefore may know better how to achieve a
given outcome. Another way to conceive of this point is that universal problems are local problems first. While drought, water theft, and crop failure may be universal problems for irrigators worldwide, each comes about through unique local circumstances. Only by occurring at many locations over time does a problem become recognized as universal and attract the attention of higher level policy-makers.

So while the results of Chapter 3 imply that the combination of flexible water allocation and rotational delivery is to be preferred over other combinations on the grounds that it produces more equal and stable outcomes without sacrificing much overall production, these may not be the criteria of interest to irrigators and it may not even be physically possible to implement these rules efficiently in a given system. Policy-makers may have good reasons believe that a certain configuration of rules will improve valued outcomes, but it is possible that such a configuration is incompatible with local norms, geography, finances, or infrastructure.

Conversely, policy-makers ought to comprehend the interactions of CPR users at greater geographic and temporal scales (Heikkila et al., 2011), possess expert knowledge and information, tend to have access to larger budgets, and have a better understanding of the outcomes that are necessary to attain broader policy goals such as climate change adaptation. In the case of allocation and distribution rules studied in Chapter 3, it is largely unprecedented in Colorado for state law to prescribe specific rules for irrigation systems. However, state law does require some institutional features of incorporated ditch companies and formally recognized acequias. It would therefore be possible to require incorporated ditch companies and
formally recognized *acequias* of a certain size to periodically evaluate their allocation and distribution rules, or any other responses to shortage, in light of a set of criteria established by law, such as equity or the prevention of excessive canal seepage losses. It could also be possible to create a less expensive alternative to water court, for some minority fraction of irrigators to petition the state engineer if they believe the voting majority is, through local rules, depriving them of their rightful allocation of water. Such an administrative hearing process would be reviewable by water court and subject to all pertinent good governance laws.

Furthermore, several government agencies – such as the Natural Resources Conservation Service – provide loans and grants to irrigation systems to implement technological and infrastructural upgrades and maintenance, and these programs could be modified to fund trial periods of institutional changes. Any financial losses incurred as a result of implementing new rules over a period of years would be paid by the programs, and irrigators could revert to old rules or keep the new ones at their discretion following the trial. In Colorado, there may even be a place for the Basin Roundtables to evaluate irrigation system performance at a larger geographic scale and bring recommendations forward for reforms of irrigation system governance, with a budget available to implement these reforms. Overall, these processes would not prescribe certain rules, but they would create opportunities for rules to be evaluated and justified in light of higher policy goals. The broad objective of policy would be to prevent local users from “locking in” maladaptive behaviors.
One unfolding example of such a legal framework is California’s Sustainable Groundwater Management Act (SGMA). Because of the scale and heterogeneity of California’s groundwater resources, it would be a practical impossibility to apply a set of panaceas to groundwater management. Instead, the state has used its technical expertise to define the boundaries of the aquifers to be managed and prioritized them according to their level of impairment. SGMA lays out six outcomes that are to be avoided or remediated through local governance of groundwater by a public body, such as land subsidence, aquifer overdraft, and reductions of streamflow resulting from groundwater pumping. The law does not prescribe specific policies that are to be used by these local public bodies to address these ills, but it does prescribe outcomes and sets a time-line for their realization depending on the aquifer’s priority. SGMA also requires certain procedural and good-governance features of the public groundwater management agencies, provides funding to facilitate planning processes, and tasks the state with creating a repository of groundwater data. Of course, if the groundwater management agencies fail to uphold the requirements of the law, the state may manage the aquifer until such a time as the local body is willing and able to fully comply. Overall, SGMA seems to have incorporated laudable features of poly-centric governance and deserves further attention from scholars and practitioners as it develops.
5.3.3. Legal Recognition of Diverse Norms and Practices Can Promote Adaptation

The final policy implication of this dissertation is that intangible factors like cultural norms play a substantial role in how policies are received and how irrigation takes place. As the American West diversifies as a result of immigration, as Native American water rights are increasingly enforced, and as younger farmers with a mind towards ecological stewardship enter farming and ranching, this point will only become more salient. Provided that diverse institutional forms of self-governance do not undermine broader policy objectives, such as climate change adaptation and equity, it is warranted to recognize and support these diverse forms. If institutions evolve as this dissertation implies, then institutional diversity is the well from which evolution draws. Without a diversity of features, there are no features which selection can promote above others. If adaptation to climate change is an evolutionary process, then homogenous institutions bode poorly for adaptation.

Furthermore, the results of Chapter 4 suggest that if there are attempts to homogenize institutional diversity, the performance of irrigation systems that find their norms at odds with law will suffer. Chapter 4 further illustrates that there were no significant differences in NDVI between acequias and Anglo systems, all else equal. This implies that broader policy goals of robust agricultural production and avoiding water waste are met by acequia governance, meaning attempts to eliminate acequia governance in the name of higher productivity are dubious.

From the perspective of irrigation in Colorado, it is appropriate then that the state has gone forward with the 2009 Acequia Recognition Law (ARL) and its 2013
ammendments. This law largely comports with the results of Chapter 4 in that, for
acequias following the process laid out in the law, some of the unique practices, values, and norms of acequias would no longer be forced into conflict with law. The law creates two formal legal statuses for acequia associations – incorproated and unincorporated – that differ from incorproated ditch companies and unincorproated mutual ditch associations. In particular, for acequias adopting bylaws stating as much, they may now legally allocate water according to methods besides pro-rata shares and they may legally make decisions based on a one-landowner-one-vote basis. Though these provisions may have been legel before the ARL, there is no longer any ambiguity about their legality. However, the law could be improved in a few ways to further align with acequia norms.

First, to better comport with norms of community governance and cooperation, the ARL could be ammended to allow for the adoption of bylaws (1) requiring permission of the acequia to install sprinklers which diminish return flows, (2) prohibiting the subdivision of existing lots without consent of the acequia, and (3) prohibiting the conversion of land-use from agriculture or conservation without consent of the acequia. These changes would vest greater authority in the hands of the acequia and recognize that due to the physical layout of land ownership and the reliance on return flows and tailwater, decisions by individuals regarding land and water on an acequia fundamentally influence the others’ abilities to irrigate their lands. This would forestall if not prevent issues reported by Cox & Ross (2011) with regards to land use change in Taos.
Second, the ARL could be amended to allow for acequias to enter into inter-system shortage sharing arrangements that more closely resemble repartimiento than the already permissible options of Interruptible Supply Plans (ISP) and Agricultural Water Leases (AWL). Such a change may require acequias to enter into agreements that voluntarily inhibit the ability of individual irrigators to fully exercise their private rights, but this would be in keeping with traditional acequia practices and norms. This would be a more difficult change because downstream users could insist on enforcing priority. But provided those downstream users formally agreed with the terms of the arrangement, it could be structured so that the arrangement required less paperwork and fees than ISPs and AWLs while building in more flexibility, mimicking repartimiento.

Third, the ARL could be amended so that acequias founded after statehood in 1876 can gain access to legal recognition. It was not until 1882 that the Colorado Supreme Court found that PA was the only legally recognized water rights regime in the state, and Hispanic irrigation systems were founded between statehood and this ruling. It is also not entirely clear that there ought to be any time restriction on the founding of the acequia and its status under the ARL, given that it is not entirely clear that the new rights conferred to acequias are expressly illegal for mutual ditch associations and incorporated ditch companies. Relaxing the requirement that the acequia be founded before statehood would allow irrigators descending from the same cultural tradition to no longer be in conflict with law if they wish to follow their historical practices.
A more transformative change that would involve going beyond the ARL, and would make implementing the above changes easier in some ways, is the formation of a "super-ditch" similar to that founded in the Lower Arkansas River Basin, where individual irrigation systems created a non-profit body to manage water between them. A major difference would be that the function would not be to lease water to cities, but instead to return water to public management in areas served by *acequias*. Such a “súper acequia” would be a non-profit corporation to which individual irrigators and *acequias* would transfer their water rights, or the right to use their water rights while still retaining the rights as individuals. The right to use the water would then be held in common between the irrigators, irrespective of priority, with each irrigator possessing equal voting power. For some decisions, it could even be that individual *acequias* would empower their *mayordomos* as their representatives within this structure, such as negotiating a *repartimiento*. Indeed, the structure could also reinstate some powers of the *alcalde* through its chief executive. It would then be possible to dispose of the water in accordance with traditional practices, provided that no downstream senior user was harmed.

A súper acequia is likely infeasible until the *acequias* individually become organized into the associations envisioned by the current ARL. It would also face many challenges, not the least of which would be ongoing legal uncertainty around the ownership of water rights in the Culebra Creek watershed in Costilla County known as the Hallett Decrees (Davidson & Guarino, 2015), as well as potential compliance issues with the Rio Grande Compact in Conejos County. Further, it may
be that state laws would need to be changed to accommodate downstream senior water right holders in some fashion. However, if achieved, a *súper acequia* would provide even greater legal protection for historic practices among *acequias*.

5.4. Concluding Thoughts on Irrigation Institutions under Climate Change

Climate change is expected to alter how successfully what crops can be grown where (Alexander et al., 2018; Challinor et al., 2014). As a result, meeting global food demand will require substantial increases in water withdrawals for irrigation (Alexander et al., 2018). However, because of limitations on the ability to expand irrigated cropland and the limitations of future water supplies, even when accounting for CO₂ fertilization, an insufficient number of calories may be produced to feed the growing population (Challinor et al., 2014; Dawson et al., 2014; Elliot et al., 2014). Furthermore, due to understudied mechanisms of plant physiology, CO₂ fertilization is expected to meaningfully decrease the zinc, iron, and protein concentrations in the edible portions of major food crops, such as maize, wheat, rice, soybeans, and field peas (Myers et al., 2014). The declines in dietary zinc and iron alone could devastate millions of lives by 2050 (Weyant et al., 2018).

Responding to this challenge in ways that not only sustain human populations but also habitat capable of supporting biodiversity will require unrelenting, targeted, coordinated, and well-resourced efforts emanating from all sectors of society at all levels of social organization. It has been the intention of this dissertation to contribute to this effort in a meaningful way, however limited, by
improving one of the most fundamental inventions supporting human life, irrigation, using one of the most flexible and rapidly evolving of human inventions, institutions. Institutions are made by human minds, and although limited in their practicality by the physical world as all human inventions are, they are limited in principle only by our collective imagination. If human beings are to avoid the worst consequences of climate change, and preserve what remains of the biodiversity our progenitors passed onto us, we must support each other in our capacity to imagine, test, and reimagine alternative governance regimes of our most precious resources, water chief among them. As the Brazilians say, “A man with water has many problems; a man without water has only one problem.”

Let us work toward a world with many problems.


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Kininmonth, S., Crona, B., Bodin, Ö., Vaccaro, I., Chapman, L. J., & Chapman, C. A. 2016. Microeconomic relationships between and among fishers and traders influence the ability to respond to social-ecological changes in a small-scale


http://doi.org/10.1093/cjres/rsq001


A1. Study Area

A1.1. Geographic Description

The San Luis Valley of Colorado is a high-altitude desert 7,000 feet above sea level where a rural community of about 50,000 irrigates 400,000-500,000 acres using snowmelt from the surrounding Rocky Mountains. From the months of November through February these is essentially no plant growth in the SLV, as temperatures are well below freezing. March sees the spring thaw, and by October nearly all crops are harvested. The valley receives little rain, just 7-10 inches annually, usually from thunderstorms in the summer, making irrigation necessary for agriculture. The economy of the SLV depends almost entirely on irrigated agriculture, and for many of the people there the struggle to grow crops is existential. Because there is no major urban center to demand water in the Rio Grande basin in Colorado, and because major trans-mountain exports have been made prohibitively expensive by geography and local opposition (Cody et al., 2015), the dynamics of agricultural systems can be explored alone, without the confounding factors introduced by significant urban and industrial users of water competing with agriculture.
A1.2. Irrigation System and Watershed Attributes

The study area consists of approximately 700 active self-governing irrigation systems. Some systems irrigate under 2 acres, some over 80,000; some have just one irrigator, others over 300. The study area contains eight major watersheds, managed as Water Districts. Overall, the Water Districts are similar with regards to the irrigation systems within them, with some exceptions. However, I do not expect these differences to negatively impact the results; on the contrary, it will only enhance the robustness and transferability of the results if variables are shown to be influential within and across watersheds with of this kind of heterogeneity. See Table A.1 for some of the key metrics of the water districts and ditch systems.

A1.3. Long-Term Climate Change in the SLV

Snowmelt dependent irrigation is expected to face significant climate change impacts (Vicuña et al., 2012; Villamayor-Tomas, 2012). Irrigators in the State of Colorado (including the SLV) face challenges to adapt to climate change: about four fifths of stream flow originates as snow in Colorado (CCC, n.d.). Colorado agriculture is dominated by user-governed canal systems: around three quarters of the cropland harvested in the state in 2013 were irrigated (USDA, 2012), and about three quarters of irrigated acres are managed by user-governed irrigation canal systems (Sax et al., 2006). Therefore, Colorado in general, and the SLV in particular, are appropriate places to test hypotheses related to user-governing irrigation systems and climate change (USBOR, 2013).
Spring snowpack is expected to decline across Colorado due to climate change, with decreasing stream flow in the SLV especially (Lukas et al., 2014). Indeed, there have already been observed changes in temperature, and therefore frost-free season and onset of peak stream flow that warrant an investigation in the SLV (Lukas et al., 2014; Mix et al., 2009; Mix et al., 2011; Mix et al., 2012). USGS streamflow data going back to the 1880s on the Rio Grande do show long-term decreases in accordance with expectations of climate change. In addition to the studies by Mix et al. (2009, 2011, 2012) on growing degree days, temperature, and runoff at the Lobatos gage on the New Mexico state line, runoff data exists going back to the 1890 on the Rio Grande in Colorado above any major diversions at the gage at Del Norte (also the gage which determines Rio Grande Compact obligations).

Using data from this gage, a simple linear regression with 95% confidence intervals shows an ongoing decline in the average daily flow over the past 100 years (Figure A.1). And when sub-setting the annual runoff data, it becomes clear that prior to 1970 the trend was towards slightly later peak runoff (Figure A.2), but that since 1970 the peak runoff has trended more steeply towards earlier peak runoff (Figure A.3). Because the major focus of this investigation is irrigation performance under climate change, and because the SLV is snowmelt limited, it is important to establish variability of snowpack and an overall declining trend. To establish the validity of the study period as analogous to expectations under climate change, Figure A.4 depicts the annual variability of snowpack and temperature from 1984-
2015 in the SLV with regression trend lines, showing increasing temperature and decreasing snowpack. Because the slopes in these figures depend on when the time-series starts and stops, they should not be interpreted as indicating climate change per se, but as evidence that the study period is analogous to expected climate change.

**A2. Methods**

**A2.1. Measures of Irrigation Performance**

There are several ways in which the performance of irrigation systems may be measured (Lam, 1998; Yu et al., 2016; Ostrom, 2005; Kadirbeyoglu & Ozertan, 2015). I use three dependent variables for each irrigation season: the length of time a system diverted water in months, the percentage of the maximum volume of water diverted over the study period, and the percentage of the maximum area irrigated over the study period. In the SLV, the State monitors and records these data. It is not possible to determine what crops are being grown using irrigated area, and therefore the value of the crops produced. However, if it is assumed that farmers are rationally growing the crops best suited for their lands, growing season, expected water supply, technology, and economic conditions (e.g. crop prices and market access), the area of irrigated land should reflect overall welfare. The other two variables should accurately reflect the degree to which water is available, and thus reveal the influence of water rights on water availability. Some studies use the amount of water applied per unit area as a measure of irrigation performance, where more water applied indicates better performance (Yu et al., 2016). However,
this is an ambiguous metric in the SLV since changes in water per unit of land reflect a decline or increase in the efficiency of water use by individual farmers at the field level, rather than a desirable increase in water delivery to the fields by the common property irrigation system. More water applied per acre may reflect wasted water, as opposed to increased agricultural production.

A2.2. Data Collection and Summaries

Most data were accessed using the Colorado Department of Natural Resources’ (DNR) Decision Support Systems website. Other data were obtained from Google Earth Engine, in particular the Digital Elevation Model from USGS which allowed for the calculation of catchment area and elevation using Geographic Information Software (GIS). Each diversion point – where water is taken from the stream and put into a gravity-fed ditch system – has a unique Water District ID (WDID) to which all relevant variables were associated. The geographic locations of these systems were also available from the DNR’s database. See Table A.1 for detailed summaries of the variables and their development.

A2.3. Data Processing

Data were processed in R version 3.3.2 and ArcGIS 10.4 unless otherwise indicated. There were 694 diversion points originally intended for inclusion in the dataset. Six diversions on Costilla Creek in Costilla County (WD24) were excluded because of insufficient data on upstream water use. Thirty-one of the remaining
diversion points lacked water rights or sufficient diversion records in the state's database, making them unusable for the study. In many cases this as because the water right which was formerly associated with this diversion point was transferred and is now associated with another diversion point that is included in the dataset. These diversion structures are given as “Historical” in the state’s database. These observations were dropped. The diversion structure might still exist, but it no longer functions as part of an irrigation system and thus does not represent a true observation. This reduced the sample to 657 diversion structures with water rights and sufficient data on which to run analyses. Finally, ArcGIS 10.4 was unable to accurately compute catchment areas for 18 additional systems, reducing the sample size to 639. Missing observations were not imputed due to the highly specific geographic and historical reasons for catchment area and water right priority values. I also did not impute the dependent variables because given the highly specific influence of geography, seasonal water flow, and water rights I am not confident that I could reasonably impute these values.

Time-variant for these observations were accessed for the years 1984-2015. The dependent variables changed over time and deserve particular attention. Using the DNR’s data for each diversion point, the total area irrigated each year was determined. The maximum value in the time series was identified, and each year’s irrigated acreage was then scaled as a percentage of this value. This was done to account for the different acreages of each system and create a comparable metric across systems. The total volume of water diverted each month was for each WDID
was also identified and summed for each year. The maximum value for the 32-year time series was identified, and each year’s diversion volume was scaled as a percentage of that value. This was done to account for the different water right flow rates of each system and create a comparable metric across systems. From the diversion data, the number of months of the calendar year in which any diversion took place was summed for each year. This variable is already comparable across systems since each experience time equally. Some error is introduced in that a single day of diversion during a month causes that month to be counted as a month of active diversion, and therefore this value represents a slight overestimate of the total diversion time.

The independent variables which changed over time were sprinkler use, reservoir use, and snow water equivalent. To generate variables appropriate for time-averaged data, the following procedures were followed. Fields irrigated using sprinklers in 1998, 2002, 2005, 2009-2015 (the only years for which data were available) were associated with their corresponding WDID. The sum of the areas of those fields was calculated and divided by the total area of fields irrigated that year to establish whether a majority of land irrigated was watered by sprinklers. If a majority of years showed a majority of sprinkler irrigated acres, this variable was coded as 1, otherwise it was coded as 0 for the entire time series. The amount of water released from reservoirs annually for the years 1983-2015 which ditch systems used to irrigate land was obtained and associated with corresponding WDID. This was reduced to an annual binary variable which, when averaged,
revealed the percentage of years in which water was received from a reservoir. Using the SNOTEL network of the USGS, SNOTEL stations with at least 15 years of data between 1983-2015 were associated with the nearest diversion point. The monthly average Snow Water Equivalent measurements were then averaged for each Water Year, which runs from October 1-September 30. For example, the 1984 SWE value is an average of October, November, and December from 1983 and the months January through September of 1984. This was done to account for the fact that snow falling in October of 1983 would not melt and provide irrigation water until the spring of 1984. The annual average SWE was then assigned to the nearest diversion point for each year in the dataset.

Once fully compiled into panel data, the variables were then averaged for each observation over the study period. Because the variable of interest, water right priority, is time-invariant, ditch-level fixed-effects model was not appropriate, and an average of the data was used to obtain an estimate of the effect, on average, of the variables of interest. A second dataset was generated to investigate the effects of water rights on irrigation performance during years with varying amounts of snowpack. The time series was subset by quintiles of SWE and averages were then calculated as above.

Once the data were averaged over time, I employed genetic matching (Diamond & Sekhon, 2013) to increase model stability and ensure comparability between the observations in the datasets (Ho et al., 2007). Genetic matching was performed using the Matching (version 4.9-2) package for R (version 3.2.1). One to
one matching with replacement was used. Population size for the optimization was set to 1000. The optimization was set to stop after four generations without improvement. Kolmogorov-Smirnov tests were done with 100 bootstraps. The variables matched on were: area, upstream ranking, elevation, groundwater access, sprinkler use on majority of land in majority of years, snow water equivalent, Water District, percent area potentially irrigated by multiple ditch systems, tributary diversion, percentage of years using a reservoir, acequia status, catchment area, and propensity score. Propensity scores were calculated using logistic regression for treatment status (water right priority ranks above the median value in each watershed). Variables used in determining the propensity score were the same as those upon which the data were matched. The matching procedure produced a dataset of 402 observations. Figure A.5 maps the included and excluded observations.

The averaged, matched data were then standardized by subtracting the mean of each variable across the 402 observations and then dividing by the standard deviation of the variable. I standardized water right ranking and upstream ranking by water district to account for the watershed dependent nature of these variables and did not standardize dichotomous variables. Standardization was done to ease interpretation and comparison of coefficients across variables of inherently different units.

See Table A.1 for more information on variable development.
A3. Data Analysis

A3.1. Software

All analyses were run in R version 3.3.2 unless otherwise indicated. Heteroscedasticity and auto-correlation robust standard errors were calculated using lmtest (version 0.9-35) (Zeileis, 2004). Regression tables were generated using stargazer (version 5.2) (Hlavac, 2015). Interactions were visualized using interflex (version 1.2) (Hainmueller et al., 2017). Effects plots were generated using effects (version 3.1-1) (Fox, 2003).

A3.2. Main Regression Model

Models without interactions on the matched, time-averaged data and the matched, time-averaged data subset by SWE took the form:

\[
\gamma_i = \beta_0 + \beta_1 PriorRank_i + \beta_2 UpRank_i + \beta_3 Trib + \beta_4 Acequa_i + \beta_5 CatchArea_i + \beta_6 Area_i \\
+ \beta_7 Elev_i + \beta_8 SWE_i + \beta_9 Res_i + \beta_{10} PerMulti_i + \beta_{11} Ground + \beta_{12} Sprink_i \\
+ \beta_{13} WD_i + \varepsilon_i
\]

When regressing the dependent variables percent maximum diversion and months of active diversion, the independent variables groundwater access, sprinkler use, and percent area irrigated by multiple ditch systems were excluded, since these would not impact those outcomes.
A3.3. Modeling Interactions

Models with interactions using the matched, time-averaged data took the following forms. When regressing the dependent variables percent maximum diversion and months of active diversion, the independent variables groundwater access, sprinkler use, and percent area irrigated by multiple ditch systems were excluded, since these would not impact those outcomes.

A3.3.1. Water Rights by Water District

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib} + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \times \text{WD}_i + \epsilon_i \]

A3.3.2. Water Rights by Tributary Diversion

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib} + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \times \text{Trib}_i + \epsilon_i \]

A3.3.3. Water Rights by Upstream Rank

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib} + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \times \text{UpRank}_i + \epsilon_i \]
A3.3.4. Water Rights by Snow Water Equivalent

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib}_i + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \ast \text{SWE}_i + \varepsilon_i \]

A3.3.5. Water Rights by Acequia Status

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib}_i + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \ast \text{Acequia}_i + \varepsilon_i \]

A3.3.6. Water Rights by Catchment Area

\[ y_i = \beta_0 + \beta_1 \text{PriorRank}_i + \beta_2 \text{UpRank}_i + \beta_3 \text{Trib}_i + \beta_4 \text{Acequia}_i + \beta_5 \text{CatchArea}_i + \beta_6 \text{Area}_i \\
+ \beta_7 \text{Elev}_i + \beta_8 \text{SWE}_i + \beta_9 \text{Res}_i + \beta_{10} \text{PerMulti}_i + \beta_{11} \text{Ground} + \beta_{12} \text{Sprink}_i \\
+ \beta_{13} \text{WD}_i + \beta_{14} \text{PriorRank}_i \ast \text{CatchArea}_i + \varepsilon_i \]

A3.4 Comparing Coefficients

Comparisons between coefficients on standardized variables were done following Cohen et al., 2003 using the following formula to compute Z-scores:

\[ Z = \frac{\beta_1 - \beta_2}{\sqrt{se^2 \beta_1 + se^2 \beta_2}} \]
Where $\beta$ are the coefficient estimates and $se\beta$ are the standard errors of the coefficient estimates. The resulting value was compared to two-tailed critical values for $p < 0.05$.

A4. Results

In marginal effects plots, the gray area represents bootstrapped 95% confidence intervals and the histogram on the x-axis shows the distribution of the moderating variable across the units of observation. In effect plots, the grey area represents computed 95% confidence intervals using heteroscedasticity and autocorrelation robust standard errors, and the vertical dashes on the x-axis represent the value of the moderating variable of individual observations (commonly called a “rug”).

For regression tables, heteroscedasticity and autocorrelation robust standard errors are reported where appropriate.
A5. Tables and Figures

**Figure A.1.** Annual mean daily flow of the Rio Grande at Del Norte, sloping downward from the 1890 to the present.

![Annual Mean Daily Flow (cfs)](image1)

**Figure A.2.** Days to peak flow on the Rio Grande at Del Norte from 1890 to 1969, nearly flat.

![Days To Peak Flow at Del Norte](image2)
Figure A.3. Days to peak flow on the Rio Grande at Del Norte from 1970 to present, sloping downward.

Figure A.4. Annual mean temperature and snowpack from 1984-2015 of all stations with at least 15 years of data.
Figure A.5. Observations in the final dataset following the removal of NAs and matching are green, those excluded are yellow. The stream network is also shown.
Figure A.6. Plot showing the marginal effect of water right priority rank over values of catchment area for percentage of maximum acres irrigated.
Figure A.7. Plot showing the marginal effect of water right priority rank over values of upstream rank for percentage of maximum acres irrigated.
Figure A.8. Plot showing the marginal effect of water right priority rank over values of snow water equivalent for percentage of maximum acres irrigated.
Figure A.9. Plot showing the effect of water right priority rank on *acequias* and non-*acequias* for percentage of maximum acres irrigated.
Figure A.10. Plot showing the effect of water right priority rank on tributary diversions and non-tributary diversions for percentage of maximum acres irrigated.

Effect of Water Right by Tributary

- Tributary 0
- Tributary 1

Water Right Priority vs. Percent Acres Irrigated
**Figure A.11.** Plot showing the marginal effect of water right priority rank over values of catchment area for percentage of maximum acre-feet diverted.
Figure A.12. Plot showing the marginal effect of water right priority rank over values of upstream rank for percentage of maximum acre-feet diverted.
Figure A.13. Plot showing the marginal effect of water right priority rank over values of snow water equivalent for percentage of maximum acres irrigated.
Figure A.14. Plot showing the effect of water right priority rank on *acequias* and non-*acequias* for percentage of maximum volume diverted.

**Effect of Water Right by Acequia**

![Graph showing the effect of water right priority rank on acequias and non-acequias for percentage of maximum volume diverted.](image-url)
Figure A.15. Plot showing the effect of water right priority rank on tributary diversions and non-tributary diversions for percentage of maximum volume diverted.
Figure A.16. Plot showing the marginal effect of water right priority rank over values of catchment area for months of active diversion.
Figure A.17. Plot showing the marginal effect of water right priority rank over values of upstream rank for months of active diversion.
Figure A.18. Plot showing the marginal effect of water right priority rank over values of snow water equivalent for months of active diversion.
Figure A.19. Plot showing the effect of water right priority rank on *acequias* and non-*acequias* for months of active diversion.

**Effect of Water Right by Acequia**

![Graph showing the effect of water right priority rank on acequias and non-acequias for months of active diversion.](image)
Figure A.20. Plot showing the effect of water right priority rank on tributary diversions and non-tributary diversions for months of active diversion.
**Table A.1.** Variable descriptions and summary statistics for the dataset following the removal of NAs and matching, but before standardizing the variables.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Measurement Summary</th>
<th>Descriptive Stats</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Independent Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Right Rank (PriorRank)</td>
<td>Water rights were ranked from most to least senior within their Water Districts, and a negative sign applied (so that the most positive value, -1, was the most senior, rather than the lowest positive value, +1, being the most senior). The earliest, or highest priority, water right for each diversion structure was associated with that diversion point.</td>
<td>N: 402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 49.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 466</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 56.21</td>
</tr>
<tr>
<td>Upstream Rank (UpRank)</td>
<td>Within each of the eight Water District, the number of diversions upstream of given diversion point (plus one, to include the system itself) was assigned to that diversion point.</td>
<td>N: 402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 33.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 144</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 38.04</td>
</tr>
<tr>
<td>Diverts from a Tributary Stream (Trib)</td>
<td>The Stream Order tool in ArcGIS 10.3 was used to calculate the stream order of each watercourse in the SLV using rasterized shapefiles from the DNR. The values ranged from 1-5. Values of 1, 2, and 3 were deemed tributaries, and values of 4 and 5 were deemed mainstems. Systems diverting water from tributaries were assigned a value of 1 for this binary variable.</td>
<td>N: 402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT ON TRIBUTARY: 24.63</td>
</tr>
<tr>
<td>Catchment Area (CatchArea)</td>
<td>Using the Hydrology toolbox in ArcGIS 10.4, watersheds of each diversion point were delineated. The areas of the shapefiles were then calculated in acres.</td>
<td>N: 402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 303</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 80,542</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 207,450</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 1,010,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 275,465</td>
</tr>
<tr>
<td><strong>Control Variables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow Water Equivalent (SWE)</td>
<td>Using the SNOTEL network of the USGS, SNOTEL stations with at least 15 years of data between 1983-2015 were associated with the nearest diversion point. The monthly average Snow Water Equivalent measurements were then averaged for each Water Year, which runs from October 1-September 30. That value was then assigned to the corresponding diversion point for each year in the dataset. For example, the 1984 SWE value is an average of October, November, and December from 1983 and the averages of the months January through September of 1984. This was done to</td>
<td>N: 402</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 1.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 5.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 6.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 12.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 2.14</td>
</tr>
</tbody>
</table>
account for the fact that snow falling in October of 1983 would not melt and provide irrigation water until the spring of 1984.

<table>
<thead>
<tr>
<th>Elevation (Elev)</th>
<th>Elevation in meters was calculated in ArcGIS 10.3 for each diversion structure using the 1/3 arc-second USGS National Elevation Dataset downloaded from Google Earth Engine.</th>
<th>N: 402</th>
<th>Min: 2292</th>
<th>Med: 2415</th>
<th>Mean: 2438</th>
<th>Max: 3192</th>
<th>SD: 107.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Majority Sprinkler in Majority of Years (Sprink)</td>
<td>Using the DNR's GIS database, fields irrigated using sprinklers in 1998, 2002, 2005, 2009-2015 were associated with their corresponding WDID. The sum of the areas of those fields was calculated and divided by the total area of fields irrigated that year to establish whether a majority of land irrigated was watered by sprinklers. If a majority of years showed a majority of sprinkler irrigated acres, this variable was coded as 1, otherwise it was coded as 0.</td>
<td>N: 402</td>
<td>PERCENT MAJORITY SPRINKLER: 8.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Years Using Surface Reservoir (Res)</td>
<td>The amount of water released from reservoirs annually for the years 1983-2015 which ditch systems used to irrigate land was obtained and associated with corresponding WDIDs. This was reduced to an annual binary variable which, when averaged, revealed the percentage of years in which water was received from a reservoir.</td>
<td>N: 402</td>
<td>Min: 0</td>
<td>Med: 0</td>
<td>Mean: 6.06</td>
<td>Max: 93.75</td>
<td>SD: 17.19</td>
</tr>
<tr>
<td>Acequia Status (Acequia)</td>
<td>Irrigation systems founded through 1940 which have Spanish names were coded as acequias. Nearly no systems with either Spanish or English names were founded after 1940.</td>
<td>N: 402</td>
<td>PERCENT ACEQUIA: 30.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acreage (Area)</td>
<td>Using the DNR's GIS data for 1998, 2002, 2005, 2009-2013, the area of the irrigated fields associated with each diversion point's WDID were summed. Thus, the largest possible area for which historical irrigation was observed was assigned to each WDID.</td>
<td>N: 402</td>
<td>Min: 1.81</td>
<td>Med: 205.75</td>
<td>Mean: 795.67</td>
<td>Max: 21967</td>
<td>SD: 2085.93</td>
</tr>
<tr>
<td>Groundwater Access (Ground)</td>
<td>Using the DNR's GIS database, any field irrigated by a groundwater well in 1998, 2002, 2005, 2009-2013 was associated with its corresponding WDID to create a binary variable indicating the presence or absence of groundwater use. Fields were related to ditch systems using surface water sources. Fields without surface water rights that are only irrigated with groundwater were excluded from this analysis.</td>
<td>N: 402</td>
<td>PERCENT WITH WELLS: 32.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Percent Area Served by Multiple Ditch Systems (PerMulti)

The total area of a system served by multiple ditch systems was computed by dividing the summed area of parcels served by multiple systems by the total area of parcels on a ditch system.

| Min: 0.0 | Med: 0.0 | Mean: 20.26 | Max: 100.00 | SD: 34.44 |

### Water District (WD)

The Water District, an administrative unit that corresponds roughly to watersheds, in which each system is located was determined. This is coded as a categorical factor. It provides information on the Rio Grande Compact, the enforcement styles of different Water Commissioners, the Closed Basin, and other factors that differ between watersheds.

| WD20: N: 116 |
| WD21: N: 45 |
| WD22: N: 65 |
| WD24: N: 30 |
| WD25: N: 48 |
| WD26: N: 61 |
| WD27: N: 21 |
| WD35: N: 16 |

### Dependent Variables

#### Months of Diversion Activity

Using the DNR’s monthly diversion data for each diversion point, the number of months of the year for which any diversion took place were summed. Some error is introduced in that a single day of diversion during a month causes that month to be counted as a month of active diversion, and therefore this value represents a slight overestimate of the total diversion time.

| N: 402 | Min: 0.138 | Med: 3.807 | Mean: 4.196 | Max: 11.161 | SD: 2.171 |

#### Percent Maximum Diversion

Using the DNR’s monthly diversion data for each diversion point, the total volume of water diverted each month was summed for each year. The maximum value for the 32-year time series was identified, and each year’s diversion volume was scaled as a percentage of that value. This was done to account for the different acreages and water right volumes of each system and create a comparable metric across systems.

| N: 402 | Min: 6.12 | Med: 42.13 | Mean: 42.83 | Max: 88.18 | SD: 18.23 |

#### Percent Maximum Irrigated Area

Using the DNR’s data for each diversion point, the total area irrigated each year was determined. The maximum value in the time series was identified, and each year’s irrigated acreage was then scaled as a percentage of this value. This was done to account for the different acreages of each system and create a comparable metric across systems.

| N: 400 | Min: 0.00 | Med: 53.86 | Mean: 55.81 | Max: 100.00 | SD: 25.62 |
Table A.2. Between estimator regression outputs for the three dependent variables.

<table>
<thead>
<tr>
<th></th>
<th>Percent Area Irrigated (1)</th>
<th>Percent Maximum Volume Diverted (2)</th>
<th>Months of Active Diversion (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.1828***</td>
<td>0.3621***</td>
<td>0.5223***</td>
</tr>
<tr>
<td></td>
<td>(0.0449)</td>
<td>(0.0381)</td>
<td>(0.0420)</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>-0.1230*</td>
<td>-0.1485**</td>
<td>-0.0933</td>
</tr>
<tr>
<td></td>
<td>(0.0688)</td>
<td>(0.0590)</td>
<td>(0.0784)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.4352***</td>
<td>-0.2576**</td>
<td>-0.0616</td>
</tr>
<tr>
<td></td>
<td>(0.1304)</td>
<td>(0.1135)</td>
<td>(0.1210)</td>
</tr>
<tr>
<td>Acequia</td>
<td>-0.0439</td>
<td>-0.0513</td>
<td>-0.1461</td>
</tr>
<tr>
<td></td>
<td>(0.1440)</td>
<td>(0.1221)</td>
<td>(0.1219)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.1768**</td>
<td>0.4785***</td>
<td>0.4261***</td>
</tr>
<tr>
<td></td>
<td>(0.0874)</td>
<td>(0.0570)</td>
<td>(0.0578)</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.0014</td>
<td>0.0809**</td>
<td>0.1323***</td>
</tr>
<tr>
<td></td>
<td>(0.0414)</td>
<td>(0.0388)</td>
<td>(0.0451)</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.0175</td>
<td>0.0296</td>
<td>0.0189</td>
</tr>
<tr>
<td></td>
<td>(0.0559)</td>
<td>(0.0512)</td>
<td>(0.0567)</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>0.1122**</td>
<td>0.0947**</td>
<td>0.1527***</td>
</tr>
<tr>
<td></td>
<td>(0.0522)</td>
<td>(0.0467)</td>
<td>(0.0492)</td>
</tr>
<tr>
<td>Percent Years Accessing Reservoir</td>
<td>0.0862*</td>
<td>0.1396***</td>
<td>0.1884***</td>
</tr>
<tr>
<td></td>
<td>(0.0517)</td>
<td>(0.0424)</td>
<td>(0.0411)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td>-0.0653</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0456)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.0621</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.1215)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler</td>
<td>-0.2940</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.2184)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 21</td>
<td>-0.3767*</td>
<td>-0.0670</td>
<td>-0.0391</td>
</tr>
<tr>
<td></td>
<td>(0.1962)</td>
<td>(0.1533)</td>
<td>(0.1580)</td>
</tr>
<tr>
<td>Water District 22</td>
<td>-0.3455*</td>
<td>0.0287</td>
<td>-0.3655**</td>
</tr>
<tr>
<td></td>
<td>(0.1803)</td>
<td>(0.1664)</td>
<td>(0.1701)</td>
</tr>
<tr>
<td>Water District 24</td>
<td>0.2881</td>
<td>0.8709***</td>
<td>1.1716***</td>
</tr>
<tr>
<td></td>
<td>(0.2371)</td>
<td>(0.2013)</td>
<td>(0.1949)</td>
</tr>
<tr>
<td>Water District 25</td>
<td>-0.7846***</td>
<td>-0.3665***</td>
<td>0.1134</td>
</tr>
<tr>
<td></td>
<td>(0.1502)</td>
<td>(0.1407)</td>
<td>(0.1732)</td>
</tr>
<tr>
<td>Water District 26</td>
<td>-1.2012***</td>
<td>-0.7605***</td>
<td>-0.0307</td>
</tr>
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</table>
### Table A.3. Between estimator regression outputs for the three dependent variables with an interaction term between water right priority and *acequia* status.

<table>
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<tr>
<th>Regression Output on Data Averaged from 1984-2015</th>
<th>Percent Area Irrigated</th>
<th>Percent Maximum Volume Diverted</th>
<th>Months of Active Diversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.1640***</td>
<td>0.3522***</td>
<td>0.4972***</td>
</tr>
<tr>
<td></td>
<td>(0.0478)</td>
<td>(0.0411)</td>
<td>(0.0437)</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>-0.1231*</td>
<td>-0.1484**</td>
<td>-0.0930</td>
</tr>
<tr>
<td></td>
<td>(0.0685)</td>
<td>(0.0590)</td>
<td>(0.0776)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.4270***</td>
<td>-0.2539**</td>
<td>-0.0522</td>
</tr>
<tr>
<td></td>
<td>(0.1307)</td>
<td>(0.1137)</td>
<td>(0.1204)</td>
</tr>
<tr>
<td>Acequia</td>
<td>-0.0864</td>
<td>-0.0735</td>
<td>-0.2023</td>
</tr>
<tr>
<td></td>
<td>(0.1518)</td>
<td>(0.1270)</td>
<td>(0.1437)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.1792**</td>
<td>0.4800***</td>
<td>0.4298***</td>
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<tr>
<td></td>
<td>(0.0871)</td>
<td>(0.0571)</td>
<td>(0.0579)</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.0004</td>
<td>0.0809**</td>
<td>0.1323***</td>
</tr>
<tr>
<td></td>
<td>(0.0404)</td>
<td>(0.0388)</td>
<td>(0.0463)</td>
</tr>
<tr>
<td>Elevation</td>
<td>0.0241</td>
<td>0.0327</td>
<td>0.0267</td>
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<tr>
<td></td>
<td>(0.0550)</td>
<td>(0.0514)</td>
<td>(0.0561)</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>0.1105**</td>
<td>0.0936**</td>
<td>0.1499***</td>
</tr>
<tr>
<td></td>
<td>(0.0519)</td>
<td>(0.0468)</td>
<td>(0.0487)</td>
</tr>
<tr>
<td>Percent Years Accessing Reservoir</td>
<td>0.0844</td>
<td>0.1392***</td>
<td>0.1872***</td>
</tr>
<tr>
<td></td>
<td>(0.0521)</td>
<td>(0.0424)</td>
<td>(0.0406)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td>-0.0694 (0.0454)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td>0.0667 (0.1213)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler</td>
<td>-0.2833 (0.2191)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 21</td>
<td>-0.3572* (0.1960) -0.0587 (0.1539) -0.0180 (0.1599)</td>
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<td></td>
</tr>
<tr>
<td>Water District 22</td>
<td>-0.3216* (0.1807) 0.0396 (0.1674) -0.3379* (0.1758)</td>
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<td></td>
</tr>
<tr>
<td>Water District 24</td>
<td>0.3254 (0.2448) 0.8911*** (0.2039) 1.2227*** (0.1963)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 25</td>
<td>-0.7778*** (0.1500) -0.3623** (0.1409) 0.1241 (0.1725)</td>
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<td></td>
</tr>
<tr>
<td>Water District 26</td>
<td>-1.1901*** (0.1276) -0.7548*** (0.1196) -0.0162 (0.1160)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 27</td>
<td>-1.3199*** (0.1860) -0.7229*** (0.1857) 0.2731 (0.2905)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 35</td>
<td>-0.5470** (0.2494) 0.1072 (0.2122) 0.4242** (0.1882)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acequia by Priority Rank</td>
<td>0.1255 (0.1131) 0.0647 (0.1011) 0.1642 (0.1677)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.5534*** (0.1003) 0.2038** (0.0810) -0.0189 (0.0819)</td>
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<td></td>
</tr>
<tr>
<td>Observations</td>
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<td></td>
</tr>
<tr>
<td>R²</td>
<td>0.3649 0.5179 0.4865</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.3313 0.4966 0.4637</td>
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<td></td>
</tr>
<tr>
<td>Residual Std. Error</td>
<td>0.8177 (df = 379) 0.7095 (df = 384) 0.7323 (df = 384)</td>
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<td></td>
</tr>
</tbody>
</table>

*Note:* *p<0.10; **p<0.05; ***p<0.01
### Table A.4. Between estimator regression for the three dependent variables with an interaction term between water right priority and tributary diversion.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Percent Area Irrigated (1)</th>
<th>Percent Maximum Volume Diverted (2)</th>
<th>Months of Active Diversion (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.2230***</td>
<td>0.4293***</td>
<td>0.5922***</td>
</tr>
<tr>
<td></td>
<td>(0.0526)</td>
<td>(0.0437)</td>
<td>(0.0481)</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>-0.1266*</td>
<td>-0.1530***</td>
<td>-0.0980</td>
</tr>
<tr>
<td></td>
<td>(0.0698)</td>
<td>(0.0584)</td>
<td>(0.0796)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.4310***</td>
<td>-0.2502**</td>
<td>-0.0540</td>
</tr>
<tr>
<td></td>
<td>(0.1291)</td>
<td>(0.1123)</td>
<td>(0.1200)</td>
</tr>
<tr>
<td>Acequia</td>
<td>-0.0645</td>
<td>-0.0873</td>
<td>-0.1835</td>
</tr>
<tr>
<td></td>
<td>(0.1432)</td>
<td>(0.1214)</td>
<td>(0.1207)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.1808*</td>
<td>0.4848***</td>
<td>0.4326***</td>
</tr>
<tr>
<td></td>
<td>(0.0926)</td>
<td>(0.0564)</td>
<td>(0.0581)</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.0019</td>
<td>0.0833**</td>
<td>0.1348***</td>
</tr>
<tr>
<td></td>
<td>(0.0406)</td>
<td>(0.0384)</td>
<td>(0.0442)</td>
</tr>
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<td>Elevation</td>
<td>0.0085</td>
<td>0.0135</td>
<td>0.0021</td>
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<td></td>
<td>(0.0545)</td>
<td>(0.0509)</td>
<td>(0.0638)</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>0.1060*</td>
<td>0.0849*</td>
<td>0.1424***</td>
</tr>
<tr>
<td></td>
<td>(0.0539)</td>
<td>(0.0464)</td>
<td>(0.0479)</td>
</tr>
<tr>
<td>Percent Years Accessing Reservoir</td>
<td>0.0784</td>
<td>0.1272***</td>
<td>0.1755***</td>
</tr>
<tr>
<td></td>
<td>(0.0492)</td>
<td>(0.0421)</td>
<td>(0.0395)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td>-0.0620</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(0.0432)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(0.1160)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprinkler</td>
<td>-0.2899</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.2099)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 21</td>
<td>-0.3773**</td>
<td>-0.0581</td>
<td>-0.0298</td>
</tr>
<tr>
<td></td>
<td>(0.1814)</td>
<td>(0.1517)</td>
<td>(0.1604)</td>
</tr>
<tr>
<td>Water District 22</td>
<td>-0.3230*</td>
<td>0.0693</td>
<td>-0.3233*</td>
</tr>
<tr>
<td></td>
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<td>(0.1652)</td>
<td>(0.1686)</td>
</tr>
<tr>
<td>Water District 24</td>
<td>0.2835</td>
<td>0.8632***</td>
<td>1.1635***</td>
</tr>
<tr>
<td></td>
<td>(0.2541)</td>
<td>(0.1992)</td>
<td>(0.1924)</td>
</tr>
<tr>
<td>Water District 25</td>
<td>-0.7995***</td>
<td>-0.3897***</td>
<td>0.0893</td>
</tr>
<tr>
<td></td>
<td>(0.1457)</td>
<td>(0.1394)</td>
<td>(0.1739)</td>
</tr>
<tr>
<td></td>
<td>Percent Maximum Area Irrigated (1)</td>
<td>Percent Maximum Volume Diverted (2)</td>
<td>Months of Active Diversion (3)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Priority Rank</td>
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<td>0.7691***</td>
<td>2.7462***</td>
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<td>(0.0989)</td>
<td>(0.0879)</td>
<td>(0.2850)</td>
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<td>Upstream Rank</td>
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</tr>
<tr>
<td></td>
<td>(0.1289)</td>
<td>(0.1100)</td>
<td>(0.3504)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.3826</td>
<td>-0.1834</td>
<td>-0.2517</td>
</tr>
<tr>
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<td>(0.2472)</td>
<td>(0.2109)</td>
<td>(0.6729)</td>
</tr>
<tr>
<td>Acequia</td>
<td>0.2382</td>
<td>0.2231</td>
<td>0.1120</td>
</tr>
<tr>
<td></td>
<td>(0.2701)</td>
<td>(0.2358)</td>
<td>(0.7512)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.3108***</td>
<td>0.6202***</td>
<td>1.5021***</td>
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<tr>
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<td>(0.1177)</td>
<td>(0.1005)</td>
<td>(0.3231)</td>
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<tr>
<td>Acreage</td>
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<td>0.0100</td>
<td>0.5185**</td>
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<td>(0.0688)</td>
<td>(0.2158)</td>
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<td>0.1085</td>
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<tr>
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<td>(0.1123)</td>
<td>(0.0929)</td>
<td>(0.2945)</td>
</tr>
<tr>
<td>Snow Water Equivalent 2002</td>
<td>0.0946</td>
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<td>0.3277</td>
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<tr>
<td></td>
<td>(0.1122)</td>
<td>(0.0965)</td>
<td>(0.3087)</td>
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Note: *p<0.10; **p<0.05; ***p<0.01

Table A.5. Tobit regression for the three dependent variables in the year 2002.
<table>
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<th>Reservoir 2002</th>
<th>1.5269***</th>
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<th>3.4008***</th>
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<td>(0.3178)</td>
<td>(0.2655)</td>
<td>(0.8520)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td>-0.1368</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(0.0940)</td>
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</tr>
<tr>
<td>Groundwater</td>
<td>0.0848</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.2042)</td>
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<td></td>
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<tr>
<td>Sprinkler</td>
<td>0.1216</td>
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</tr>
<tr>
<td></td>
<td>(0.3255)</td>
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<td></td>
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<tr>
<td>Water District 21</td>
<td>-0.6816*</td>
<td>-0.6830**</td>
<td>-1.5929*</td>
</tr>
<tr>
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<td>(0.3594)</td>
<td>(0.2938)</td>
<td>(0.9429)</td>
</tr>
<tr>
<td>Water District 22</td>
<td>-1.5575***</td>
<td>-1.4339***</td>
<td>-3.4055***</td>
</tr>
<tr>
<td></td>
<td>(0.4270)</td>
<td>(0.3685)</td>
<td>(1.1758)</td>
</tr>
<tr>
<td>Water District 24</td>
<td>-0.8789*</td>
<td>-0.1631</td>
<td>0.0782</td>
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<td>(0.4694)</td>
<td>(0.3801)</td>
<td>(1.2119)</td>
</tr>
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<td>Water District 25</td>
<td>-0.6598**</td>
<td>-0.4092</td>
<td>-0.1982</td>
</tr>
<tr>
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<td>(0.3216)</td>
<td>(0.2768)</td>
<td>(0.8788)</td>
</tr>
<tr>
<td>Water District 26</td>
<td>-1.2098***</td>
<td>-0.9614***</td>
<td>-1.3651*</td>
</tr>
<tr>
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<td>(0.2729)</td>
<td>(0.2364)</td>
<td>(0.7522)</td>
</tr>
<tr>
<td>Water District 27</td>
<td>-1.3711***</td>
<td>-1.0233***</td>
<td>-0.7303</td>
</tr>
<tr>
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<td>(0.4462)</td>
<td>(0.3781)</td>
<td>(1.1521)</td>
</tr>
<tr>
<td>Water District 35</td>
<td>0.0919</td>
<td>0.7030*</td>
<td>2.6881**</td>
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<tr>
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<td>(0.4466)</td>
<td>(0.3596)</td>
<td>(1.1529)</td>
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<tr>
<td>logSigma</td>
<td>0.2854***</td>
<td>0.1428***</td>
<td>1.3128***</td>
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<td>(0.0516)</td>
<td>(0.0529)</td>
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<td>(0.1577)</td>
<td>(0.5080)</td>
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<td>398</td>
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<td>Akaike Inf. Crit.</td>
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<td>Bayesian Inf. Crit.</td>
<td>1,021.0250</td>
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<td>1,477.9097</td>
</tr>
</tbody>
</table>

*Note:* *p<0.10; **p<0.05; ***p<0.01
Table A.6. Between estimator regression outputs for percent acres irrigated across five subsets of SWE.

<table>
<thead>
<tr>
<th>Percent Acres Irrigated</th>
<th>Regression Output for the Between Estimator of Percent Acres Irrigated Subset by Snowpack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Dry (1)</td>
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<tr>
<td>Priority Rank</td>
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</tr>
<tr>
<td></td>
<td>0.2368***</td>
</tr>
<tr>
<td></td>
<td>(0.0447)</td>
</tr>
<tr>
<td>Upstream Rank</td>
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</tr>
<tr>
<td></td>
<td>-0.1799**</td>
</tr>
<tr>
<td></td>
<td>(0.0718)</td>
</tr>
<tr>
<td>Tributary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.4818***</td>
</tr>
<tr>
<td></td>
<td>(0.1334)</td>
</tr>
<tr>
<td>Acequia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0574</td>
</tr>
<tr>
<td></td>
<td>(0.1410)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2650***</td>
</tr>
<tr>
<td></td>
<td>(0.0879)</td>
</tr>
<tr>
<td>Acreage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0108</td>
</tr>
<tr>
<td></td>
<td>(0.0371)</td>
</tr>
<tr>
<td>Elevation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.0327</td>
</tr>
<tr>
<td></td>
<td>(0.0442)</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1330**</td>
</tr>
<tr>
<td></td>
<td>(0.0587)</td>
</tr>
<tr>
<td>Percent of Years Using a Reservoir</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0981*</td>
</tr>
<tr>
<td></td>
<td>(0.0535)</td>
</tr>
<tr>
<td>Percent Acreage Potentially Irrigated by Multiple Ditch Systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.0534</td>
</tr>
<tr>
<td></td>
<td>(0.0434)</td>
</tr>
<tr>
<td>Groundwater</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0411</td>
</tr>
<tr>
<td></td>
<td>(0.1097)</td>
</tr>
<tr>
<td>Sprinkler</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.2249</td>
</tr>
<tr>
<td></td>
<td>(0.1774)</td>
</tr>
<tr>
<td>Water District 21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.3695**</td>
</tr>
<tr>
<td></td>
<td>(0.1761)</td>
</tr>
<tr>
<td>Water District 22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.3646*</td>
</tr>
<tr>
<td></td>
<td>(0.2022)</td>
</tr>
<tr>
<td>Water District 24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2492</td>
</tr>
</tbody>
</table>
### Table A.7. Between estimator regression outputs for percent maximum diversion across five subsets of SWE.

<table>
<thead>
<tr>
<th>Percent Maximum Diversion</th>
<th>Very Dry</th>
<th>Dry</th>
<th>Intermediate</th>
<th>Wet</th>
<th>Very Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.3845*** (0.0404)</td>
<td>0.3748*** (0.0400)</td>
<td>0.3328*** (0.0389)</td>
<td>0.2123*** (0.0482)</td>
<td>0.2615*** (0.0432)</td>
</tr>
<tr>
<td>Upstream Rank</td>
<td>-0.1818** (0.0705)</td>
<td>-0.1875*** (0.0680)</td>
<td>-0.1188** (0.0600)</td>
<td>-0.1536* (0.0800)</td>
<td>-0.0428 (0.0731)</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.1813 (0.1147)</td>
<td>-0.2392** (0.1177)</td>
<td>-0.1402 (0.1158)</td>
<td>-0.4178*** (0.1484)</td>
<td>-0.1917 (0.1456)</td>
</tr>
<tr>
<td>Acequia</td>
<td>0.1378 (0.1232)</td>
<td>-0.0474 (0.1312)</td>
<td>-0.0463 (0.1247)</td>
<td>0.0141 (0.1564)</td>
<td>-0.2310 (0.1567)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.5911*** (0.0628)</td>
<td>0.5454*** (0.0644)</td>
<td>0.4172*** (0.0581)</td>
<td>0.3530*** (0.0650)</td>
<td>0.2130*** (0.0734)</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.0318 (0.0609)</td>
<td>0.0150 (0.0584)</td>
<td>0.0591 (0.0392)</td>
<td>0.1319*** (0.0400)</td>
<td>0.1490*** (0.0486)</td>
</tr>
<tr>
<td>Elevation</td>
<td>-0.0511 (0.0511)</td>
<td>-0.0413 (0.0511)</td>
<td>0.0145 (0.0511)</td>
<td>0.1447** (0.0511)</td>
<td>0.1062 (0.0511)</td>
</tr>
</tbody>
</table>
### Table A.8. Between estimator regression outputs for months of active diversion across five subsets of SWE.

<table>
<thead>
<tr>
<th>Months of Active Diversion</th>
<th>Very Dry (1)</th>
<th>Dry (2)</th>
<th>Intermediate (3)</th>
<th>Wet (4)</th>
<th>Very Wet (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority Rank</td>
<td>0.4992***</td>
<td>0.5119***</td>
<td>0.5251***</td>
<td>0.4467****</td>
<td>0.4992***</td>
</tr>
<tr>
<td></td>
<td>(0.0445)</td>
<td>(0.0430)</td>
<td>(0.0408)</td>
<td>(0.0460)</td>
<td>(0.0421)</td>
</tr>
</tbody>
</table>

Regression Output for the Between Estimator of Months of Active Diversion Subset by Snowpack

<table>
<thead>
<tr>
<th>Observations</th>
<th>402</th>
<th>402</th>
<th>402</th>
<th>402</th>
<th>402</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>0.5193</td>
<td>0.5256</td>
<td>0.4968</td>
<td>0.2966</td>
<td>0.3381</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.4994</td>
<td>0.5059</td>
<td>0.4759</td>
<td>0.2674</td>
<td>0.3106</td>
</tr>
<tr>
<td>Residual Std. Error (df = 385)</td>
<td>0.7076</td>
<td>0.7029</td>
<td>0.7239</td>
<td>0.8559</td>
<td>0.8303</td>
</tr>
</tbody>
</table>

Note: *p<0.10; **p<0.05; ***p<0.01
<table>
<thead>
<tr>
<th>Component</th>
<th>Estimate 1</th>
<th>Estimate 2</th>
<th>Estimate 3</th>
<th>Estimate 4</th>
<th>Estimate 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Rank</td>
<td>-0.1344**</td>
<td>-0.1377*</td>
<td>-0.1055</td>
<td>-0.0536</td>
<td>-0.0190</td>
</tr>
<tr>
<td>Tributary</td>
<td>-0.0691</td>
<td>-0.1437</td>
<td>-0.0537</td>
<td>-0.0165</td>
<td>-0.0172</td>
</tr>
<tr>
<td>Acequia</td>
<td>-0.1258</td>
<td>-0.2137*</td>
<td>-0.1810</td>
<td>-0.0320</td>
<td>-0.1178</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>0.4730***</td>
<td>0.4832***</td>
<td>0.3988***</td>
<td>0.3676***</td>
<td>0.3189***</td>
</tr>
<tr>
<td>Acreage</td>
<td>0.1353***</td>
<td>0.0908***</td>
<td>0.1216***</td>
<td>0.1599***</td>
<td>0.1552***</td>
</tr>
<tr>
<td>Elevation</td>
<td>-0.0021</td>
<td>-0.0081</td>
<td>0.0050</td>
<td>0.0307</td>
<td>0.0724</td>
</tr>
<tr>
<td>Snow Water Equivalent</td>
<td>0.1681***</td>
<td>0.1707***</td>
<td>0.1482***</td>
<td>0.1431**</td>
<td>0.1113**</td>
</tr>
<tr>
<td>Percent of Years Using a</td>
<td>0.1534***</td>
<td>0.1741***</td>
<td>0.1681***</td>
<td>0.2148***</td>
<td>0.1609***</td>
</tr>
<tr>
<td>Reservoir</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water District 21</td>
<td>-0.0946</td>
<td>-0.0675</td>
<td>-0.0980</td>
<td>-0.0373</td>
<td>0.1145</td>
</tr>
<tr>
<td>Water District 22</td>
<td>-0.3675**</td>
<td>-0.2980*</td>
<td>-0.4917***</td>
<td>-0.4684**</td>
<td>-0.0160</td>
</tr>
<tr>
<td>Water District 24</td>
<td>1.0573***</td>
<td>1.2774***</td>
<td>1.1420***</td>
<td>1.0079***</td>
<td>0.9864***</td>
</tr>
<tr>
<td>Water District 25</td>
<td>0.0714</td>
<td>0.1530</td>
<td>-0.0484</td>
<td>0.2276</td>
<td>0.1100</td>
</tr>
<tr>
<td>Water District 26</td>
<td>-0.2278*</td>
<td>-0.2599*</td>
<td>-0.1080</td>
<td>0.2137*</td>
<td>0.1827</td>
</tr>
<tr>
<td>Water District 27</td>
<td>0.2735</td>
<td>0.0084</td>
<td>0.1274</td>
<td>0.6798**</td>
<td>0.3458</td>
</tr>
<tr>
<td>Water District 35</td>
<td>0.4260*</td>
<td>0.5209***</td>
<td>0.3466</td>
<td>0.3154</td>
<td>0.4954**</td>
</tr>
<tr>
<td>Constant</td>
<td>0.0411</td>
<td>0.0606</td>
<td>0.0751</td>
<td>-0.0892</td>
<td>-0.1225</td>
</tr>
<tr>
<td>Observations</td>
<td>402</td>
<td>402</td>
<td>402</td>
<td>402</td>
<td>402</td>
</tr>
<tr>
<td>R²</td>
<td>0.4647</td>
<td>0.4934</td>
<td>0.4683</td>
<td>0.4110</td>
<td>0.3964</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.4425</td>
<td>0.4723</td>
<td>0.4462</td>
<td>0.3866</td>
<td>0.3713</td>
</tr>
<tr>
<td>Residual Std. Error (df = 385)</td>
<td>0.7467</td>
<td>0.7264</td>
<td>0.7442</td>
<td>0.7832</td>
<td>0.7929</td>
</tr>
</tbody>
</table>

Note: *p<0.10; **p<0.05; ***p<0.01
APPENDIX A BIBLIOGRAPHY


**B1. Study Area Description**

*B1.1. Geographic description*

The San Luis Valley of Colorado is a high-altitude desert, 7,000 feet above sea level, where a rural community of about 50,000 irrigates 400,000-500,000 acres using snowmelt from the surrounding Rocky Mountains. The valley receives little rain, just 7-10 inches annually, making irrigation necessary for agriculture. The economy of the SLV depends almost entirely on irrigated agriculture, and for many of the people there the struggle to grow crops is existential. Because the SLV is a headwaters system, because there is no major urban center to demand water in the Rio Grande basin in Colorado, and because major trans-mountain exports have been made prohibitively expensive by geography and local opposition (Cody et al., 2015), the dynamics of agricultural systems can be explored alone, without the confounding factors introduced by significant urban and industrial users of water competing with agriculture and upstream use dynamics.

*B1.2. Irrigation System, Field, and Year Attributes*

The study area consists of approximately 700 active self-governing irrigation systems. A stratified sample of 60 systems was collected in the Summer of 2013. Of
the 60 sampled, systems irrigate anywhere from 30 to over 115,000 acres and have between 1 and over 300 irrigators. Major crops grown include alfalfa, grass pasture, small grains, potatoes, and other minor crops such as vegetables. Fields themselves range in size from less than an acre to over 750 acres. The study runs from 2011-2014, a period of well below average stream flow (Table B.1). The years 2011, 2012, and 2014 are included as robustness checks; the rules being analyzed were assessed in 2013, and are assumed to have been in place in 2011, 2012, and 2014. See Table A.7 for an overview of the variables included in the analysis. See Table B.1 for a summary of the key independent variables used in the analysis across the years of the study broken out by the institutional configurations under consideration. See Figure B.1 for a color-coded map of the irrigation systems sampled and their institutional configurations.

Table B.1. Summary of independent variables of interest for each institutional configuration.

<table>
<thead>
<tr>
<th>Institutional Group</th>
<th>Total Sampled</th>
<th>Ave. Max. Dist. (km)</th>
<th>Ave. AF/Acre 2011</th>
<th>Ave. AF/Acre 2012</th>
<th>Ave. AF/Acre 2013</th>
<th>Ave. AF/Acre 2014</th>
<th>Ave. AF/Acre 2011-2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneous, Not Sharing</td>
<td>13</td>
<td>9.687</td>
<td>1.943</td>
<td>1.753</td>
<td>1.873</td>
<td>2.060</td>
<td>1.91</td>
</tr>
<tr>
<td>Simultaneous, Sharing</td>
<td>11</td>
<td>17.037</td>
<td>3.209</td>
<td>1.905</td>
<td>1.855</td>
<td>3.762</td>
<td>2.68</td>
</tr>
<tr>
<td>Rotation, Not Sharing</td>
<td>8</td>
<td>6.739</td>
<td>1.054</td>
<td>1.166</td>
<td>0.870</td>
<td>1.753</td>
<td>1.21</td>
</tr>
<tr>
<td>Rotation, Sharing</td>
<td>28</td>
<td>10.879</td>
<td>1.769</td>
<td>1.736</td>
<td>2.021</td>
<td>3.026</td>
<td>2.14</td>
</tr>
<tr>
<td>Overall</td>
<td>60</td>
<td>11.198</td>
<td>1.975</td>
<td>1.694</td>
<td>1.805</td>
<td>2.765</td>
<td>2.06</td>
</tr>
</tbody>
</table>
Figure B.1. A simplified map of the sampled irrigation systems, color-coded for their institutional configuration.
B1.3. Long-Term Climate Change in the SLV

Spring snowpack is expected to decline across Colorado due to climate change, with decreasing stream flow in the Rio Grande basin especially (Lukas et al., 2014). Indeed, there have already been observed changes in temperature, and therefore frost-free season and onset of peak stream flow that warrant an investigation in Colorado’s Rio Grande Basin (Lukas et al., 2014; Mix et al., 2009; Mix et al., 2011; Mix et al., 2012). USGS streamflow data going back to the 1880s on the Rio Grande do show longer term decreases in accordance with expectations of climate change. In addition to the studies by Mix et al. (2009, 2011, 2012) on growing degree days, temperature, and runoff at the Lobatos gage on the New Mexico state line, runoff data exists going back to the 1890 on the Rio Grande in Colorado above any major diversions at the gage at Del Norte (also the gage which determines Rio Grande Compact obligations).

Because the major focus of this investigation is irrigation performance under climate change, and because the SLV is snowmelt limited, it is important to establish variability of snowpack and an overall declining trend. To establish the validity of the recent past as analogous to expectations under climate change, Figure B.2 depicts the annual variability of snowpack and temperature in the study area with regression trend lines. These should not be interpreted as indicating climate change per se, but as evidence that the recent past is analogous to expected climate change.
Figure B.2. Annual mean temperature and snowpack from 1984-2015 of all stations with at least 15 years of data.

During the study period, 2011-2014, snowpack has been well below normal, as illustrated by Figure B.3 and Table B.2.

Figure B.3. Snowpack in the SLV from 2011-2014, showing below normal volume, earlier peak, and earlier melt (NRCS, n.d.).
Table B.2. Summary of the irrigation seasons analyzed, showing that snowpack, streamflow, and percentage of acreage irrigated were below average in each year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Irrigation Conditions and Outcomes</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percent of Average Snow Water Equivalent</td>
<td>96.5</td>
<td>67.5</td>
<td>62.2</td>
<td>84.5</td>
</tr>
<tr>
<td></td>
<td>Average of Upstream Gages Percent of Average</td>
<td>66.1</td>
<td>56.6</td>
<td>48.5</td>
<td>83.9</td>
</tr>
<tr>
<td></td>
<td>Average Months of Active Diversion</td>
<td>4.13</td>
<td>4.08</td>
<td>4.47</td>
<td>4.88</td>
</tr>
<tr>
<td></td>
<td>Average Percent Maximum Diversion</td>
<td>39.5</td>
<td>35.5</td>
<td>35.8</td>
<td>52.3</td>
</tr>
<tr>
<td></td>
<td>Average Acre-feet Diverted per Acre</td>
<td>1.98</td>
<td>1.69</td>
<td>1.80</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td>Average Percent Acres Irrigated</td>
<td>62.3</td>
<td>57.2</td>
<td>62.2</td>
<td>74.1</td>
</tr>
</tbody>
</table>

Data from the 1880s to the present show a decrease in streamflow on the Rio Grande. Changes in temperature, frost-free season, growing degree days, and onset of peak stream flow have already been observed in the SLV (Mix et al., 2011; Mix et al., 2012), These changes call for an investigation into the effects of climate change on irrigated agriculture in the SLV. Important for this analysis, streamflow at the nearest upstream gages of the self-governing irrigation systems that were sampled was well below average in the years 2011-2013, with 2014 being slightly below average.

B2. Water Rights, Rules-In-Use, and Climate Change Adaptation

Adapting irrigated agriculture to climate change in the SLV and elsewhere will be contextually dependent on the incumbent water rights regime. In the SLV, this regime is known as Prior Appropriation (PA) (Adler, 2010; Kenney, 2005). PA is the dominant or exclusive regime of water allocation in Colorado, the rest of the
Western United States, Australia, and Western Canada. It is generally inflexible during shortage (Howe et al., 1982), with the exception that it is possible (though costly and slow) to sell or lease water rights. Under Colorado’s version of this system, water right holders are ranked on a priority list determined by the order in which their water rights were adjudicated by the state’s Water Court; this is often summarized as “first in time, first in right”. When there is not enough water available to satisfy all water right holders, entities with the most recent (“junior”) rights, are curtailed or denied water entirely so that those with the oldest and therefore most “senior” rights can divert their full allocation. In practice, this means that senior users are able to divert their full right for longer periods of time than junior users, who may be limited to a matter of days or weeks or receive no water at all. This poses significant challenges for all except the most senior water rights holders during drought. Thus, in the SLV, although the weather-induced shortage that different irrigation systems experience may be similar in a given year, they experience different levels of legal water shortage.

Prior Appropriation creates persistent inequalities between irrigation systems. Over time PA leads to the failure of farms on junior systems and consolidation of ownership, where farmers on senior ditch systems buy land and water rights on junior ones. And while this is a profitable system for seniors, it discourages efficiency by senior users who are guaranteed their full allocation, leading to lost potential profits throughout the system. A strict application of the PA system also discourages the highest marginal return on water use by depriving
juniors of the ability to farm entirely so that seniors can improve crop vigor (Howe et al., 1982). Unique return flow dynamics can lead to externalities when transfers occur in water markets (Howe et al., 1982). In addition, PA has no inherent place for environmental uses of water, posing challenges for ecosystem integrity under a water constrained future; only in the past 40 to 20 years have in stream flows and non-consumptive recreational uses been incorporated into Colorado water law. Prior Appropriation may therefore be working against risk mitigation and may exacerbate inequalities and vulnerabilities in the overall agricultural sector. However, because of the strong vested interests and legal framework surrounding PA, it is unlikely to be meaningfully altered.

The unique features of PA aside, other water rights regimes in operation around the world also produce differential outcomes (Dinar, et al., 1997). In drought, some if not all irrigation systems inevitably divert less water than they normally would. Climate change will exacerbate this by challenging established institutional arrangements. Existing centralized adaptive management regimes may be too slow to respond to the pace of change and increase in variability. New institutional arrangements may be needed in order to imbed more rapid adaptations at local and regional levels that respond to change independent from central governing authorities. Even in a developed economy in a state with secure property rights to water, self-governed irrigation systems are challenged to adapt to their changing environments (Cox, 2014; Fernald et al., 2012), and these challenges result in varying irrigation performance (Cox & Ross, 2011; Janssen & Anderies,
2013). Are there micro-level institutions, i.e. rules in use adopted by irrigators which limit behavior under threat of sanction (Ostrom, 1990), that irrigators can design among themselves that may mitigate against the risks associated with climate change and an externally enforced, relatively inflexible, and harsh private property rights regime? Put another way, how do different institutional configurations adopted by self-governing irrigation systems influence irrigation performance in drought?

This paper argues that self-governance can be used to improve irrigation performance during drought. Micro-institutions are some of the few things irrigators can control beyond their land, and so they are vital as a first response to drought. Other potential changes are more expensive and disruptive to implement. Cultural norms are resistant to change and evolve slowly (Poteete et al., 2010). Technological and infrastructural changes are expensive and can have unintended consequences (Lam, 1998). Legislative changes, such as those to an incumbent water rights regime, usually challenge powerful vested interests, may be too general, and often have effects that go beyond what is intended (Ostrom, 2005). In contrast, user-originated rules in use are less expensive to change, voluntarily adopted, tailored to local conditions and norms, and relatively reversible. These rules in use affect users’ economic incentives and signal to users the relative social costs and benefits of certain behaviors (Ostrom, 2005). In doing so, they make some outcomes more likely and others less likely.
B3. Shortage Sharing, Rotational Delivery, and Adaptations to Scarcity

Two universal micro-institutional features of self-governing irrigation systems – water allocation rules and water distribution rules – are especially worthy of study due to their direct and fundamental influence on water use (Ostrom, 1992). Water allocation rules pertain to how much water each farmer within an irrigation system gets, and distribution rules determine how that water reaches the farmer. Table B.3 summarizes the rules which are the focus of this study: whether water allocations can be changed between individual irrigators on the same irrigation system (“shortage sharing”), and whether water is distributed to individual irrigators on the same irrigation system in a rotation or simultaneously. Important for the SLV is the fact that water rights are administered by the state at the point where water is diverted from the natural water source through a human-made diversion structure and into the human-made irrigation system. Beyond the diversion structure, the state does not interfere with how water is administered on the irrigation system except to enforce contracts.

<table>
<thead>
<tr>
<th>Rules in Use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simultaneous Delivery</strong></td>
<td>After the diversion structure is opened, water flows down the main canal and both into and past individual farmer's headgates. Each individual receives water by a unit of volume per unit time (e.g. cubic feet per second [cfs]). Those with rights to divert water into their farm and field level distribution system do so at the same time.</td>
</tr>
<tr>
<td><strong>Rotational Delivery</strong></td>
<td>After the diversion structure is opened, water flows down the main canal and into only one or a defined group of individual farmer’s headgates. Each individual or group receives water by a unit in time (e.g. days). After the de facto water right is exhausted, another individual or group receives water for their turn in a predefined order.</td>
</tr>
<tr>
<td><strong>No Shortage Sharing</strong></td>
<td>There is no mechanism to change how water is allocated to users, and de facto water rights are not changed in scarcity.</td>
</tr>
<tr>
<td><strong>Shortage Sharing</strong></td>
<td>There is a mechanism to change how water is allocated to users, and de facto water rights do change in scarcity.</td>
</tr>
</tbody>
</table>
Figure B.4 helps understand how irrigation unfolds. There are many criteria used to allocate water in the SLV and globally, including: underlying private water rights, shares of ownership in an irrigation company, amount of land owned, crop water demand, the need to water animals, user contributions to maintenance and fees, and need based on family size, among other criteria (Dinar et al., 1997).

**Figure B.4.** Diagram of two simplified irrigation systems. System 1 is upstream of System 2, as the water flows left to right. Two diversion dams of different sizes and quality allow water into the main canal or ditch. Water is then either delivered simultaneously to all users’ laterals or delivered in a rotation to groups of users (e.g. lateral canals) or individuals, suffering seepage losses along the way. This water is allocated based on some *de facto* property right. But, if property rights are flexible, then this is deemed “shortage sharing”, and users may change allocations between each other. After water has been allocated, delivered, and applied, it may run off the field onto another field or back into the ditch, seep into the ground, or enter a drain that takes the runoff into a river or another ditch.

**Simplified Irrigation System Diagrams**

In response to drought, the amount of water allocated to irrigators that derives from the above criteria can be changed to share the burden of shortage. Sharing shortage in this study is defined as “changed water allocations” between
members of a given irrigation system, which means that de facto property rights are flexible on that system. This corresponds to exchanges within System A and within System B in Figure B.4. This is in contrast to the sort of shortage sharing conducted by irrigation systems studied by Smith (2016) and Cox (2010) in New Mexico where irrigation systems change allocations between each other in an inter-system arrangement (i.e. between System 1 and System 2 in Figure B.4).

The intra-system shortage sharing that is the focus of this study can range in complexity from bilateral agreements between irrigators (e.g. between A and C on System 1 from Figure B.4), to multilateral agreements between several irrigators (e.g. between A, B, and D on System 1 from Figure B.4), and to agreements with all irrigators on the irrigation system involved (e.g. between A, B, C, and D on System 1 from Figure B.4). These agreements range from ad hoc and temporary to planned in advance and long-term, and from informal handshakes to formal, written exchanges. Potential benefits of shortage sharing include allocating water to the most productive land, providing farmers with water when crops are stressed, ensuring continued cooperation of farmers, and giving farmers flexibility with their assets. Some potential drawbacks include altered hydraulic head within the canal system, modified seepage losses, modified return flows, unclear allocations among irrigators, increased monitoring costs, and negotiation costs to establish and alter the shortage sharing arrangements.

In addition to allocation rules in use, distribution rules in use are also fundamental. Irrigation systems must have some rule for delivering water once the
available water is allocated. Distribution rules can also be adapted to drought conditions. Globally and in the SLV, distribution tends to occur in one of two ways (Dinar, et al., 1997). In one, simultaneous delivery, water is delivered the full length of canal system to be divided among users at the same time. In Figure B.4, it would be as if A, B, C, and D on System 1 could remove their rightful rate of flow from the ditch as the water flowed past their headgates. In the other form of delivery, rotational delivery, the full flow is sent to individual farmers or groups of individuals. This would be as if water were sent, in turns of hours or days or even weeks, in some order, to the numbered laterals on System 2 from Figure B.4. Some self-governing irrigation systems always rotate, regardless of hydrologic conditions, and in shortage those systems may change the rotation or not.¹ In shortage, if any change in the form of delivery takes place at all, systems tend to switch from simultaneous delivery to a rotation. Potential benefits of rotation are that it may generate the necessary hydraulic head to push water the length of the ditch system, minimize seepage losses, ease monitoring of water use, affirmatively require delivery to all users, and ensure that enough water is delivered to saturate the root zone of crops. The potential drawbacks of rotation are that it can be costly to negotiate, requires more work and infrastructure investment to operate than simultaneous delivery, can deliver unequal amounts of water over equal amounts of

¹ In this study, sampled irrigation systems had the opportunity to indicate whether the rotation itself changed as well as whether water allocations could be changed. Only those who answered that allocations did change were counted as sharing shortage.
time, and may be wasteful if individual farmers receive more water than they can use efficiently during their turn in the rotation.

Indeed, rotation (with or without) shortage sharing has the problem of potentially having too few or too many turns during very dry years. Sending water the full length of the ditch first, as many do in order to assure the most tail-end farmer that their best chance to receive water, may prove futile and thus waste quite a bit of water. Any turn taking that does not proceed from the top to the bottom of the ditch will cause inefficient wetting of the ditch bed. Also, for some crops, it may be better to get water continuously for 30 days than just two or three times, even though pulses of flow from rotation are more efficient over a given area for a given amount of water. When pulsing with low flows and a long time between pulses, soil may lose a great deal of water in the time between turns, stressing the crops and limiting growth. Finally, if a farmer anticipates three turns but is somehow only able to get two turns in the rotation, this may be devastating. Delivering water continuously may not be optimal hydrologically, but if it is lower risk, farmers may still use it and implement other adaptations such as on-farm storage to generate pulse flows, crop changes, groundwater wells, or more efficient irrigation.

To further illustrate the connection between these rules, consider the case where delivery is normally simultaneous and shortage sharing is taking place: the user taking a cut is in fact delivering a “pulse”, or increased flow rate, of water for however long the shortage sharing arrangement is in effect – be that days, weeks,
or the entire season. If the arrangement takes place more than once in a season, or at a defined interval, this amounts to the rotation of the pulse. At the extreme, this pulse becomes the full flow of the ditch, which is rotated between users or groups of users. Under such a full rotation, all users but one or a few take no water for a given period, which can be seen as the result of extreme, temporary, mutual, and repeated changes in allocation (i.e. shortage sharing). And while some systems follow a full rotation at all times, and on its own this may have effects on performance that differ from simultaneous delivery, if shortage sharing is also taking place this necessarily changes the rotation itself; to allow for different final allocations of water, the delivery schedules must be altered (e.g. for irrigator X to receive more water than would otherwise be the case, irrigator X would have to start their turn in the rotation earlier). All this is to say that it is better to evaluate the effect of shortage sharing while considering its interaction with delivery.

The four institutional configurations that are possible by combining the shortage sharing and delivery rules have different implications for return flows, seepage, hydraulic head, transaction and monitoring costs, and equity, among other factors. Table B.4 gives a summary of some of the implications of the four combinations of allocation and delivery rules in shortage. These implications could lead to divergent irrigation performance, measured in this study at the level of the individual irrigated field by three variables: a binary variable that measures whether a field was irrigated or not (i.e. fallowed), the percentage of a field’s area
that was irrigated, and the Normalized Difference Vegetation Index (NDVI) of a field (a proxy for photosynthesis and therefore intensity of crop growth).

Table B.4. The projected hydrological, operational, and negotiation implications of four different institutional configurations. The degree to which these hydrological, operational, and negotiation impacts actually affect irrigation performance is unclear, and will likely depend on contextual factors such as the size of the irrigation system, its soils, its average slope, the degree of formal organization, the skill of individual irrigators, how water is normally allocated, the quality of infrastructure, and the cultural norms of irrigators, among others.

<table>
<thead>
<tr>
<th>Implications for System</th>
<th>Hydrology</th>
<th>Monitoring and Operations</th>
<th>Negotiations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simultaneous, No Shortage Sharing</strong></td>
<td>1) Divided hydraulic head, 2) higher seepage loss, 3) unlikely to deliver more water than can be used, 4) return flows, hydraulic head, and seepage unaltered by shortage sharing</td>
<td>1) No affirmative delivery requirement, 2) difficult to monitor all users at once, 3) cheap to operate, 4) easy to know who is owed what, 5) crops cannot be salvaged</td>
<td>None</td>
</tr>
<tr>
<td><strong>Simultaneous, Shortage Sharing</strong></td>
<td>1) Divided hydraulic head, 2) higher seepage loss, 3) unlikely to deliver more water than can be used, 4) shortage sharing may alter return flows, hydraulic head, and seepage</td>
<td>1) No affirmative delivery requirement, 2) difficult to monitor all users at once, 3) cheap to operate, 4) potentially difficult to know who is owed what, 5) transfers straightforward to execute, 6) crops can be salvaged</td>
<td>Bilateral to whole ditch</td>
</tr>
<tr>
<td><strong>Rotation, No Shortage Sharing</strong></td>
<td>1) Concentrated hydraulic head, 2) lower seepage loss, 3) potentially delivers more water than can be used, 4) return flows, hydraulic head, and seepage unaltered by shortage sharing</td>
<td>1) Affirmative delivery requirement, 2) easy to monitor one user at a time, 3) costly to operate, 4) easy to know who is owed what, 5) crops cannot be salvaged</td>
<td>None to whole ditch</td>
</tr>
<tr>
<td><strong>Rotation, Shortage Sharing</strong></td>
<td>1) Concentrated hydraulic head, 2) lower seepage loss, 3) sharing improves efficiency of rotation, reducing waste, 4) shortage sharing may alter return flows, hydraulic head, and seepage</td>
<td>1) Affirmative delivery requirement, 2) easy to monitor one user at a time, 3) costly to operate, 4) potentially difficult to know who is owed what, 5) taking turns complicates transfers, 6) crops can be salvaged</td>
<td>Bilateral to whole ditch</td>
</tr>
</tbody>
</table>

This study advances the literature by considering the combined effects on irrigation performance of shortage sharing and delivery method. There are
numerous studies that separately investigate shortage sharing (D’Exelle et al., 2013; He et al., 2012; Torell & Ward, 2010; Ward et al., 2013) and rotation (Abdullaev et al., 2006; Janssen et al., 2012; Turral et al., 2002). Further complicating this literature, there is not agreement as to what constitutes shortage sharing. D’Exelle et al. (2013) investigated instances where head-enders forego diversions with the intention of enabling tail-enders to irrigate (thus reducing the head-ender diversions disproportionately), finding that while this reduced efficiency, it improved equity. Ward et al. (2013) and Torell & Ward (2010) assessed various shortage sharing arrangements, finding that an equal percentage reduction in diversions by all irrigators was flexible, easily understood, and enhanced crop production as compared to shortage arrangements that applied unequal risk burdens. He et al. (2012) also studies several mechanisms of shortage sharing under PA in Alberta, Canada where changes to water allocations were made through various inflexible rules as well as markets. They found that all modes of shortage sharing were efficiency improvements over PA, with market exchanges being the most efficient. The overall message from the literature regarding shortage sharing is that it is beneficial, especially when it is congruent with contributions to system maintenance, allocates shortage risk equitably, and is agreed upon in a transparent manner between all members of the irrigation system (Bernard et al., 2013; Dayton-Johnson, 2000; Torell & Ward, 2010; Ward et al., 2013).

The results of rotation are similar, in that it accomplishes the goals it is implemented to achieve: rotational delivery has been found to improve equity
between the head-end and tail-end (Abdullaev et al., 2006; Trral et al., 2002). Indeed, irrigators in the SLV directly stated in interviews that this was the intention of rotation. While Janssen et al. (2012) does not make this finding in an experimental setting, the rotational delivery mechanism was not accompanied by enforcement of any maximum diversion duration or amount, was not negotiated by the irrigators, and the effect of rotation was not the focus of the study. Additionally, rotation was selected by 2/3 of the experimental groups of real-world irrigators in Janssen et al. (2012), possibly because irrigators understand that rotation is an effective, equitable, or at least familiar mechanism of water delivery. This does not mean that rotation is necessarily efficiency enhancing or improves crop production in the short term in aggregate, only that, under a well-functioning rotational system, the most vulnerable irrigators seem to be spared from the worse consequences of drought, in part because there is at least a de jure affirmative requirement to deliver water to every rightful irrigator for at least some duration of time – farmers in the SLV have been known to stay up all night just to be sure they get their full turn, especially if that turn lasts only hours.

While these findings are important and meaningful, the state of the literature is problematic because these two rules-in-use – allocation and distribution – are at work simultaneously and jointly influence how water moves through the physical ditch system. The effect on irrigation performance of shortage sharing likely depends on whether rotation is taking place, and the effect on irrigation performance of rotation also likely depends on whether shortage sharing
is taking place. Hydrologically, shortage sharing necessarily alters how delivery takes place, and delivery necessarily alters what shortage sharing arrangements are possible (the use of turns complicates transfers); for a changed allocation to take effect, the water must be delivered in a way that changes water flow in the ditch from the pre-sharing agreement state.

Compounding the difficulty of assessing the influence of these rules-in-use is that their influence should be impacted by the degree of water scarcity and the distance a field is from the diversion structure of the irrigation system. In extreme shortage, tail-enders should be the most stressed due to seepage losses, depressed hydraulic head, and decreased return flows (Lam, 1998). Furthermore, the lack of an affirmative delivery requirement under a simultaneous delivery system can lead to “stationary bandit” behavior of head-enders (Janssen et al., 2011; Janssen et al., 2012) who use their position as the “first in line” to over-extract from the commons. However, because irrigators require ongoing collective action to maintain and operate their canal systems, it is unlikely that tail-enders would be fully deprived of water even in extreme scarcity. Depriving tail-enders of water entirely could result in damaging retaliation (gossip, sabotage, physical confrontation, etc.) and a costly decline in cooperation over time (e.g. refusal to pay fees, monitor water use, contribute labor, etc.) (Dayton-Johnson, 2000; Janssen et al., 2012; Pérez, et al., 2016). As shortage worsens, the importance of these physical heterogeneities and the differences between of rules-in-use on irrigation performance should become more pronounced (Torell & Ward, 2010; Ward et al., 2013). The interactions
between the rules-in-use and physical context are complicated and their results difficult to predict, but it is reasonable to hypothesize that these interactions are meaningful for irrigation performance.

**B4. Measures of Irrigation System Performance**

There are several ways in which the performance of irrigation systems may be measured (Lam, 1998; Yu et al., 2016; Ostrom, 2005; Kadirbeyoglu & Ozertan, 2015). Because of the limits of the available data and the desire to use a replicable methodology, one of my dependent variables is that of Cox & Ross (2011) and Smith (2016), who use multi-band satellite imagery converted to Normalized Difference Vegetation Index (NDVI) to assess crop growth in Taos, New Mexico. While it is not possible to determine what crops are being grown using NDVI, and therefore the value of the crops produced, there is ongoing use of this measurement in the literature on irrigation (Zwart & Leclert, 2010; Li et al., 2004). If it is assumed that farmers are rationally growing the crops best suited for their soils, expected water supply, technology, and economic conditions (e.g. crop prices and market access), the intensity of crop growth as captured by NDVI should reflect overall welfare. For contexts where subsistence is of more relevance than market prices, NDVI would have even more analytical value since the overall production of crops is directly linked to survival. I assess maximum crop growth, or peak greenness, using the maximum month’s NDVI as representative of the harvest in a given year.
Additionally, irrigation systems can be assessed not only for their ability to grow crops – the ultimate end of irrigation – but for their ability to apply that water to their acreage (Lam, 1998). In the SLV, the State monitors and records acreage data, and thus this study also assesses performance on this criterion. A binary irrigated/fallowed indicator is also used for each field. Some studies use the amount of water applied per unit area as a measure of irrigation performance, where more water applied indicates better performance (Yu et al., 2016). However, I lack data on the volume applied to each field. I do have the volume diverted into each ditch system and the overall acreage of that system, but for my purposes here this measure is more appropriate for representing the overall availability of water in a given year than performance.

**B5. Analytical Framework**

To analyze rules in use, I employ the IAD framework. This follows Cox (2010) and Smith (2016), who use the IAD framework in their work in similar and geographically proximate self-governing irrigation systems in New Mexico. The IAD framework is useful for analyzing institutions in a SES because it clearly defines and separates variable concepts and can work with multiple theories (Sabatier, 2007). I also employ CPR theory (Ostrom, 1992; Cox, 2010; Wilson et al., 2013), which is designed to understand the management of a resource that is difficult to exclude people from using and that is depleted by its use, such as an irrigation system. CPR theory has demonstrated ability to explain outcomes in experimental,
survey, and field studies of irrigation systems (Ostrom, 2005; Poteete et al., 2010). CPR theory is especially useful in this study for identifying control variables such as irrigation system acreage, irrigation technology, and cultural heritage.

B6. Methods

B6.1. Irrigation manager survey

Interviewees were identified using data from the Colorado Department of Natural Resources’ (DNR) Decision Support Systems website. Each ditch system has a unique Water District ID (WDID) to which all relevant variables were associated. Table B.5 shows how WDIDs were stratified.

Table B.5. Summary of stratified sample groups.

<table>
<thead>
<tr>
<th>Sample Group</th>
<th>Total Sampled</th>
<th>Rotating not Sharing</th>
<th>Sharing and Simultaneous</th>
<th>Rotating and Sharing</th>
<th>Simultaneous not Sharing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junior, Downstream, Ground</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Junior, Downstream, No Ground</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Junior, Upstream, Ground</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Junior, Upstream, No Ground</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Senior, Downstream, Ground</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Senior, Downstream, No Ground</td>
<td>17</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Senior, Upstream, Ground</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Senior, Upstream, No Ground</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
WDIDs were grouped based on their priority rank (above/below the median ranking in their watershed), stream location (above/below the median ranking in their watershed), and groundwater access (1/0). Additional subgroupings were made based on acreage (above/below the median ranking in the basin), and acequia status (1/0). Finally, an effort was made to balance the sample across Water Districts (WD). A random number was then assigned to every WDID, and the WDIDs within each stratified group were sorted based on this random number. The Office of the State Engineer was then contacted for assistance in contacting the WDIDs of interest, which were selected by moving down the random numbers from lowest to highest. The State Engineer contacted the Water Commissioners, who are responsible for monitoring water rights in each WD and have contact with leaders of each WDID. The Water Commissioners contacted the WDIDs of interest, and those willing to participate were scheduled for an interview.

The survey was conducted over two, two-week sampling bouts in May and June of 2013. The instrument was developed in concert with community leaders in the SLV to address questions they had as well as make theoretical abstractions more meaningful for irrigators. Surveys were administered face to face at a location of the interviewee’s choosing by two to three researchers at a time, with one researcher leading the questioning and writing down answers, and the others taking notes and confirming accurate recording of responses. Each night after samples were collected the research groups came together to align their understanding of the responses and to identify where improvements to the
instrument and its administration could be made. To ensure that questions were being asked the same way by different researchers, the groups of researchers were mixed each day, if not multiple times each day, and discrepancies were quickly and retroactively addressed. The average administration time was approximately 60 minutes. The surveys were conducted in English. Table B.5 shows the distribution of the institutional configurations per stratified sample group. See Section B10 for the text of the questions and available responses used in this analysis.

**B6.2. Variable development and summaries**

Data were accessed using the Colorado Department of Natural Resources’ (DNR) Decision Support Systems website and gathered from an irrigation manager surveys administered in Summer 2013. Each ditch system has a unique Water District ID (WDID) to which all relevant variables were associated. Each irrigated field (denoted as a parcel) was given a unique Master ID (MID) and had ditch level information applied to it. The geographic locations of these diversion structures, irrigation footprints, and fields were also available from the DNR’s GIS database. Data were processed in R version 3.3.2 and ArcGIS 10.4 unless otherwise indicated. Some data, such as snowpack and streamflow, could not be applied directly to irrigation systems or fields. In these cases, the nearest weather station or stream gage provided the data for the irrigation system. See Table B.7 for detailed summaries of the variables used.
Two independent variables of interest in the hypotheses are water availability and field distance from diversion. The volume of water diverted by the irrigation system per acre of irrigable land on that system is used to assess water availability to irrigators. It represents the most proximate measurement possible of water entering the irrigation system from the water source. It is a measure that is comparable across systems of different sizes, and is agriculturally relevant since different crops in the SLV require a certain amount of water per acre, usually between 2-4 acre-feet (Henderson, 1979a, 1979b). Field distance from diversion is measured as a straight line from the centroid of the field to the diversion structure. This approximates the distance that water must flow through the canals, ditches, and laterals to reach the field, but in all cases it is an underestimate. The measure for each field is scaled as a percentage of the largest distance a field is from the diversion of a given irrigation system. This makes the variable comparable across systems of different sizes.

Table B.7. Variable descriptions and summary statistics.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Measurement Summary</th>
<th>Descriptive Stats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Variables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field Distance from Diversion (DIV_DIST)</td>
<td>Using ArcGIS 10.4 and the DNR’s GIS database, the distance from each field to the diversion structure that irrigates it was calculated. For each ditch system, the maximum distance was determined. Each field on each system was then scaled as a percentage of that system’s maximum distance.</td>
<td>N: 6711</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 55.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 54.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 100.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 22.06</td>
</tr>
<tr>
<td>Changes Water Allocations in Shortage (SHR_SRC)</td>
<td>Systems reporting that they make some change to how water is allocated between members during shortage were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT SHARING SHORTAGE: 65.00</td>
</tr>
<tr>
<td>Parameter</td>
<td>Description</td>
<td>Code/Calculation Details</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Rotates Water Delivery in Shortage (ROT_SRC)</td>
<td>Systems reporting that they rotate water delivery during shortage were coded as 1.</td>
<td></td>
</tr>
<tr>
<td>Acrefeet Diverted per Acre (AFDIV_PERDACRE)</td>
<td>Using the DNR's database, the total volume of water diverted each year by each WDID was divided by total acreage of the fields that could be irrigated.</td>
<td>N: 239 Min: 0.00 Med: 1.27 Mean: 2.06 Max: 13.41 SD: 2.34</td>
</tr>
<tr>
<td>Control Variables</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field Acreage (BASEACRES)</td>
<td>Using the DNR’s GIS database and ArcGIS 10.4, each MID had its area calculated.</td>
<td>N: 6711 Min: 0.06 Med: 24.81 Mean: 54.65 Max: 759.86 SD: 59.79</td>
</tr>
<tr>
<td>Crop (CROP)</td>
<td>Using the DNR’s GIS database, each MID was assigned the crop it grew in a given year. All cereals besides corn were coded as Small Grains. New Alfalfa was coded as Alfalfa. All other crops were coded as Other.</td>
<td>Alfalfa: 9752 Grass Pasture: 10928 Potatoes: 2262 Small Grains: 2960 Other: 298</td>
</tr>
<tr>
<td>Water Right Rank (WDPRIOR)</td>
<td>Water rights were ranked from most to least senior within their Water Districts, and a negative sign applied (so that the most positive value, -1, was the most senior, rather than the lowest positive value, +1, being the most senior). The earliest, or highest priority, water right for each diversion structure was associated with that diversion point.</td>
<td>N: 60 Min: 1 Med: 24.50 Mean: 52.03 Max: 311 SD: 65.83</td>
</tr>
<tr>
<td>Field Distance to Stream (STRM_DIST)</td>
<td>Using ArcGIS 10.4 and the DNR’s GIS database, the distance from each field to the nearest natural water body was calculated.</td>
<td>N: 6711 Min: 0.00 Med: 2018.60 Mean: 2734.20 Max: 11488.00 SD: 2488.75</td>
</tr>
<tr>
<td>Slope (SLOPE)</td>
<td>Using the DNR’s GIS database, the 1/3 arc-second USGS National Elevation Dataset downloaded from Google Earth Engine, and ArcGIS 10.4, the slope of each irrigation ditch was calculated.</td>
<td>N: 60 Min: 0.08 Med: 0.46 Mean: 0.67 Max: 5.37</td>
</tr>
<tr>
<td>Field Acreage as Percent of Total Acreage (ACREPER)</td>
<td>The area of the MID was scaled as a percentage of the WDID's total acreage.</td>
<td>N: 6711</td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 0.000407</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 0.150320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 0.894050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 100.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 0.79</td>
</tr>
<tr>
<td>Historical Percent of the Irrigation System's Maximum Acreage Irrigated (PERMAXACIRRAVE)</td>
<td>The annual percentage of the maximum acreage irrigated by that WDID in the DNR's database averaged from 1984-2015.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 2.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 66.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 67.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 116.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 18.72</td>
</tr>
<tr>
<td>Historical Percent of Average Streamflow (PERAVAFGAGE)</td>
<td>The nearest stream gage upstream of a given WDID was used to calculate the percent of the historical average for that gage in the years 2011-2014. This was done using the entire range of years for which data were available for that gage.</td>
<td>N: 240</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min: 6.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Med: 62.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean: 61.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 100.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD: 25.31</td>
</tr>
<tr>
<td>Sprinkler Use (SPRINK)</td>
<td>Using the DNR's GIS database, any field irrigated using a sprinkler in a given year was coded as 1.</td>
<td>N: 26844</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT USING SPRINKLERS: 31.23</td>
</tr>
<tr>
<td>Monitoring Agent (MONITOR)</td>
<td>Systems reporting that they have a dedicated monitoring agent, either a “ditch rider” or “mayordomo” were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT WITH MONITOR: 55.00</td>
</tr>
<tr>
<td>Sole User (SOLEUSER)</td>
<td>Systems reporting a membership of 1 were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT SOLE USER: 11.67</td>
</tr>
<tr>
<td>Water Allocated Based on Land Owned or Need (LANDNEED)</td>
<td>Systems reporting that water is allocated to members according to the amount of land they own or their need were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT ALLOCATING WATER BASED ON LAND OWNED OR NEED: 21.67</td>
</tr>
<tr>
<td>Access to a Surface Reservoir (RES)</td>
<td>Systems reporting access to a reservoir were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT WITH RESERVOIR: 41.67</td>
</tr>
<tr>
<td>Acequia Status (ACEQUIA)</td>
<td>Irrigation systems which have Spanish names or were confirmed by locals as acequias were coded as 1.</td>
<td>N: 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PERCENT ACEQUIA: 53.33</td>
</tr>
</tbody>
</table>

258
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>N: 60</th>
<th>PERCENT WITH PROBLEMATIC INFRASTRUCTURE: 40.00</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ditch System Incorporated (INC)</strong></td>
<td>Systems which reported being incorporated or appeared in the Secretary of State's database of registered corporations were coded as incorporated.</td>
<td></td>
<td>40.00</td>
</tr>
<tr>
<td><strong>Infrastructure Problematic (INFRA)</strong></td>
<td>On a scale of 1-5, systems reporting challenges with infrastructure on a level of 3, 4, or 5 were coded as having problematic infrastructure.</td>
<td>N: 60</td>
<td>40.00</td>
</tr>
<tr>
<td><strong>Soil Quality Problematic (SOIL)</strong></td>
<td>On a scale of 1-5, systems reporting challenges with soil quality on a level of 3, 4, or 5 were coded as having problematic soils.</td>
<td>N: 60</td>
<td>23.33</td>
</tr>
<tr>
<td><strong>Southern Aspect (SOUTH)</strong></td>
<td>Using the Digital Elevation Model available from USGS and the irrigation system boundaries available from the DNR, the average aspect of each irrigation system was calculated with ArcGIS 10.3. Southwest, South, and Southeast were all considered as facing South to create a binary variable.</td>
<td>N: 60</td>
<td>20.00</td>
</tr>
<tr>
<td><strong>Acreage (DACRES)</strong></td>
<td>Using the DNR’s GIS data, the area susceptible to irrigation by a given WDID was accessed.</td>
<td>N: 60</td>
<td></td>
</tr>
<tr>
<td><strong>Groundwater Access (GROUND)</strong></td>
<td>Using the DNR’s GIS database, any field irrigated by a groundwater well in a given year was coded as 1.</td>
<td>N: 26844</td>
<td>42.39</td>
</tr>
<tr>
<td><strong>Field Served by Multiple Ditch Systems (MULTD)</strong></td>
<td>The total number of ditch systems irrigating an MID were determined. Systems with more than one ditch system irrigating it were coded as 1.</td>
<td>N: 6711</td>
<td>19.74</td>
</tr>
<tr>
<td><strong>Change to Rotation (CNG2ROT)</strong></td>
<td>Systems reporting that they change their delivery mechanism from simultaneous delivery to rotational delivery were coded as 1.</td>
<td>N: 60</td>
<td>16.00</td>
</tr>
<tr>
<td><strong>Source Stream (WATER_SRC)</strong></td>
<td>The surface stream each irrigation system diverts water from was accessed from the DNR’s GIS database.</td>
<td>N: 60</td>
<td></td>
</tr>
</tbody>
</table>

### Source Stream (WATER_SRC)
- RIO GRANDE: 13
- CONEJOS RIVER: 10
- ALAMOSA RIVER: 7
- LA JARA CREEK: 6
- CULEBRA: 5
- SAN ANTONIO RIVER: 4
- SAN FRANCISCO: 3
- RITO ALTO: 2
### Dependent Variables

<table>
<thead>
<tr>
<th>Dependent Variables</th>
<th>Description</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Percent Maximum Irrigated Area (PERIRR)</strong></td>
<td>Using the DNR’s data for each MID, the total largest footprint of the field was calculated. Each year’s irrigated acreage was then scaled as a percentage of this value.</td>
<td>N: 26844&lt;br&gt;Min: 0.00&lt;br&gt;Med: 70.99&lt;br&gt;Mean: 50.92&lt;br&gt;Max: 100.00&lt;br&gt;SD: 45.66</td>
</tr>
<tr>
<td><strong>Maximum Monthly Average NDVI (NDVI)</strong></td>
<td>Monthly NDVI rasters were accessed from Google Earth Engine using LandSat images from USGS. Each month from January 2011 through December 2014 was evaluated for cloud cover, presence of frost, and overall quality. Months deemed of sufficient quality were downloaded and loaded into ArcGIS 10.4. In conjunction with a rasterized version of the field level GIS data representing unique MIDs, the average NDVI value for each system in each month of each year of the study period was calculated using Zonal Statistics after setting values less than 0.3 (unirrigated) to 0. The maximum monthly value was assigned to the MID. Although not all years in the time series contain the same number of months, within each year each MID has the same number of months included in its annual average, making this average comparable across systems.</td>
<td>N: 26844&lt;br&gt;Min: 0.000&lt;br&gt;Med: 0.489&lt;br&gt;Mean: 0.455&lt;br&gt;Max: 0.883&lt;br&gt;SD: 0.260</td>
</tr>
<tr>
<td><strong>Irrigated/Fallowed (IRRDUM)</strong></td>
<td>If any portion of the MID was irrigated, this value was coded as 1.</td>
<td>N: 26844&lt;br&gt;&lt;br&gt;PERCENT IRRIGATED: 57.71</td>
</tr>
</tbody>
</table>

### B7. Data Analysis

All analyses were run in R version 3.3.2 unless otherwise indicated. Cluster robust standard errors were calculated using multiwayvcov (version 1.2.3) (Graham
et al., 2016). Logistic models were estimated using the glm function in the base stats package (version 3.3.2). Tobit models were estimated using censReg (version 0.5-26) (Henningsen, 2017). Regression tables were generated using stargazer (version 5.2) (Hlavac, 2015). Spatial error and spatial lag models were fit using spdep (version 0.6-12) (Bivand & Piras, 2015). Effects plots were generated using effects (version 3.1-2) (Fox, 2003).

**B8. Results**

**B8.1. Summary of Regressions**

Table B.8 shows significant differences between head-end and tail-end fields in extreme, moderate, and minor shortage from 2011-2014. Table B.9 shows irrigation performance under extreme vs. slight shortage at the head-end, mid-reach, and tail-end of the irrigation system from 2011-2014.
Table B.8. Head-end vs. tail-end in extreme, moderate, and minor shortage, displaying overall inequality of outcomes between the head and tail end as water availability increases. Text that is bolded, underlined, or italicized indicates a significant difference (p < 0.1) between head-enders (0% maximum distance from diversion) and tail-enders (100% maximum distance from diversion) at the given shortage levels: extreme (833 cubic meters per hectare), moderate (4900 cubic meters per hectare), and minor (10600 cubic meters per hectare). A caret (^) indicates that tail-enders outperform head-enders. Bolded years indicate a significant difference in that year when the dependent variable is binary: fallowed or irrigated. Italicized years indicate a significant difference in that year when the dependent variable is the percentage of area irrigated. Underlined years indicate a significant difference in that year when the dependent variable is NDVI. The more modified the text, the more reliable the signal. Given the number of regressions performed, there is a very high chance that some significant differences are Type I errors. Therefore, positive results for years seeing only one DV show significant differences should be taken as tenuous. Rotation shows its ability to equalize head and tail enders under almost all conditions, while simultaneous delivery with shortage sharing generates the most consistent inequality, especially in extreme shortage.

<table>
<thead>
<tr>
<th>Institutional Arrangement</th>
<th>Head enders significantly different from tail enders in extreme shortage (833 cubic meters per hectare)?</th>
<th>Head enders significantly different from tail enders in moderate shortage (4900 cubic meters per hectare)?</th>
<th>Head enders significantly different from tail enders in minor shortage (10600 cubic meters per hectare)?</th>
</tr>
</thead>
</table>
Table B.9. Irrigation performance under extreme vs. slight shortage at the head-end, mid-reach, and tail-end of the irrigation system, displaying overall inequality of marginal productivity between the head and tail end as water availability increases. Text that is bolded, underlined, or italicized indicates a significant difference ($p < 0.1$) between extreme (0 cubic meters per hectare) and slight shortage (12,335 cubic meters per hectare) at the given distance from the diversion structure. A caret (^) indicates that more water produces significantly worse outcomes. **Bold** years indicate a significant difference in that year when the dependent variable is binary: fallowed or irrigated. *Italicized* years indicate a significant difference in that year when the dependent variable is the percentage of the total area irrigated. **Underlined** years indicate a significant difference in that year when the dependent variable is NDVI. The more modified the text, the more reliable the signal. Given the number of regressions performed, there is a very high chance that some significant differences are Type I errors. Therefore, positive results for years seeing only one DV show significant differences should be taken as tenuous. Rotation with shortage sharing shows its ability to improve outcomes equally up and down the ditch as more water becomes available, something simultaneous delivery fails to do for the tail-end. Shortage sharing with simultaneous delivery is the weakest arrangement when it comes to allocating increased water supplies to produce increased crop growth.

<table>
<thead>
<tr>
<th>Institutional Configuration</th>
<th>Extreme shortage significantly different from slight shortage for head end (5%)?</th>
<th>Extreme shortage significantly different from slight shortage for mid ditch (50%)?</th>
<th>Extreme shortage significantly different from slight shortage for tail end (95%)?</th>
</tr>
</thead>
</table>
Table B.10 shows the Variance Inflation Factor (VIF) of each variable in the regression model without any interactions for NDVI in the years 2011-2014. VIF evaluates whether multicollinearity is a threat to the model. VIFs less than 5 warrant little to no concern, between 5 and 10 warrant some concern, and greater than 10 are concerning. In cases where categorical variables have more than two levels, it is very common for these variables to be correlated with each other due to being mutually exclusive. However, these VIFs are not a concern for estimation. Overall, these VIF values indicate there is not a problem with multicollinearity despite some control variables having greater uncertainty in their parameter estimates. Thankfully, they are not the independent variables of interest.


<table>
<thead>
<tr>
<th>Variable</th>
<th>VIF 2014</th>
<th>VIF 2013</th>
<th>VIF 2012</th>
<th>VIF 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler Use</td>
<td>3.8278152</td>
<td>3.7518914</td>
<td>3.7578638</td>
<td>3.7866480</td>
</tr>
<tr>
<td>Crop: Grass Pasture</td>
<td>1.6414125</td>
<td>1.6765613</td>
<td>1.7166795</td>
<td>1.7684032</td>
</tr>
<tr>
<td>Crop: Other</td>
<td>1.1343632</td>
<td>1.0960616</td>
<td>1.0985822</td>
<td>1.0914590</td>
</tr>
<tr>
<td>Crop: Potatoes</td>
<td>1.5198280</td>
<td>1.4360847</td>
<td>1.5152300</td>
<td>1.4679550</td>
</tr>
<tr>
<td>Crop: Small Grains</td>
<td>1.3610961</td>
<td>1.3370532</td>
<td>1.3435003</td>
<td>1.4167290</td>
</tr>
<tr>
<td>Groundwater Well</td>
<td>2.2351588</td>
<td>2.1668657</td>
<td>2.1553746</td>
<td>2.1724131</td>
</tr>
<tr>
<td>Percent Average at Upstream Gage</td>
<td>16.6775318</td>
<td>10.9307354</td>
<td>13.6427771</td>
<td>21.0036279</td>
</tr>
<tr>
<td>Water Source: Alamosa River</td>
<td>5.9920485</td>
<td>4.1420704</td>
<td>6.3086494</td>
<td>4.8427458</td>
</tr>
<tr>
<td>Water Source: Conejos River</td>
<td>19.9043486</td>
<td>13.9524251</td>
<td>11.2981428</td>
<td>10.2829619</td>
</tr>
<tr>
<td>Water Source: Costilla</td>
<td>1.4698980</td>
<td>1.4204287</td>
<td>1.5636878</td>
<td>1.5492016</td>
</tr>
<tr>
<td>Water Source: Culebra</td>
<td>6.4711663</td>
<td>7.4042719</td>
<td>6.0503322</td>
<td>4.6649999</td>
</tr>
<tr>
<td>Water Source: Kerber Creek</td>
<td>1.1721786</td>
<td>1.1502459</td>
<td>1.4740857</td>
<td>1.207849</td>
</tr>
<tr>
<td>Water Source: La Jara Creek</td>
<td>3.2518961</td>
<td>2.2520512</td>
<td>2.7539889</td>
<td>3.3051075</td>
</tr>
<tr>
<td>Water Source: Rito Alto Creek</td>
<td>1.5839317</td>
<td>1.8635004</td>
<td>1.5817257</td>
<td>1.8352106</td>
</tr>
<tr>
<td>Water Source: Rito Seco</td>
<td>1.4054535</td>
<td>1.3906791</td>
<td>1.3646354</td>
<td>1.3737055</td>
</tr>
<tr>
<td>Water Source: San Antonio River</td>
<td>7.0245113</td>
<td>2.2926309</td>
<td>3.5966255</td>
<td>3.4865761</td>
</tr>
<tr>
<td>Water Source: San Francisco</td>
<td>1.8417101</td>
<td>1.6786916</td>
<td>1.7830160</td>
<td>1.7335238</td>
</tr>
<tr>
<td>Water Source: San Luis Creek</td>
<td>2.1456019</td>
<td>1.9003231</td>
<td>3.9746922</td>
<td>2.2001832</td>
</tr>
<tr>
<td>Water Source: Sangre de Cristo Creek</td>
<td>NA</td>
<td>9.7486174</td>
<td>10.8513777</td>
<td>23.5955826</td>
</tr>
<tr>
<td>Water Source: Torcido</td>
<td>1.7273416</td>
<td>1.6307968</td>
<td>1.6208106</td>
<td>1.634547</td>
</tr>
<tr>
<td>Water Source: Vallejos</td>
<td>3.9177703</td>
<td>3.9554984</td>
<td>3.7000088</td>
<td>3.2501843</td>
</tr>
<tr>
<td>Water Source: Ventero Creek</td>
<td>1.3252967</td>
<td>1.4121848</td>
<td>1.2727628</td>
<td>1.2945855</td>
</tr>
<tr>
<td>Reservoir Access</td>
<td>4.7193526</td>
<td>4.4707373</td>
<td>5.2348221</td>
<td>4.3144140</td>
</tr>
<tr>
<td></td>
<td>7.2731918</td>
<td>7.6214630</td>
<td>7.4329210</td>
<td>7.4146055</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Soil Problematic</strong></td>
<td>1.8037757</td>
<td>1.7840165</td>
<td>1.8107214</td>
<td>1.8010993</td>
</tr>
<tr>
<td><strong>Irrigated by Multiple Ditches</strong></td>
<td>4.0522881</td>
<td>3.7161624</td>
<td>4.2561767</td>
<td>4.1306042</td>
</tr>
<tr>
<td><strong>Infrastructure Problematic</strong></td>
<td>5.2949085</td>
<td>4.6644303</td>
<td>6.5031044</td>
<td>5.4208852</td>
</tr>
<tr>
<td><strong>Water Allocated on Land or Need</strong></td>
<td>6.4224089</td>
<td>9.3429774</td>
<td>7.1679891</td>
<td>7.237939</td>
</tr>
<tr>
<td><strong>Acequia Status</strong></td>
<td>6.5678125</td>
<td>6.6484557</td>
<td>6.5970076</td>
<td>6.8194917</td>
</tr>
<tr>
<td><strong>South Facing Aspect</strong></td>
<td>4.5435582</td>
<td>4.1737216</td>
<td>4.216460</td>
<td>4.6552427</td>
</tr>
<tr>
<td><strong>Slope</strong></td>
<td>4.0504562</td>
<td>5.0812529</td>
<td>5.0460654</td>
<td></td>
</tr>
<tr>
<td><strong>Field Distance from Stream</strong></td>
<td>1.7735953</td>
<td>1.8099913</td>
<td>1.8111702</td>
<td>1.8032552</td>
</tr>
<tr>
<td><strong>Field Acreage</strong></td>
<td>2.3151555</td>
<td>2.3471280</td>
<td>2.3251827</td>
<td>2.3385247</td>
</tr>
<tr>
<td><strong>Field/Ditch Area Ratio</strong></td>
<td>2.7596787</td>
<td>2.6098236</td>
<td>2.5714253</td>
<td>2.5955805</td>
</tr>
<tr>
<td><strong>Ditch Area</strong></td>
<td>8.6554965</td>
<td>8.9267421</td>
<td>8.5877171</td>
<td>8.5814276</td>
</tr>
<tr>
<td><strong>Water Right Priority Rank</strong></td>
<td>2.9711476</td>
<td>3.2147216</td>
<td>3.2944396</td>
<td>3.1580603</td>
</tr>
<tr>
<td><strong>Percent Maximum Area Irrigated on Average</strong></td>
<td>4.6054443</td>
<td>5.3652499</td>
<td>6.0826844</td>
<td>4.8909644</td>
</tr>
<tr>
<td><strong>Monitoring Agent</strong></td>
<td>3.4964531</td>
<td>3.2299231</td>
<td>3.6496256</td>
<td>3.5894548</td>
</tr>
<tr>
<td><strong>Change to Rotation in Shortage</strong></td>
<td>9.4516778</td>
<td>10.7399566</td>
<td>10.4255103</td>
<td>10.4403282</td>
</tr>
<tr>
<td><strong>Shortage Sharing</strong></td>
<td>4.8418098</td>
<td>6.0573840</td>
<td>5.0105858</td>
<td>5.0553329</td>
</tr>
<tr>
<td><strong>Rotate in Scarcity</strong></td>
<td>4.9944195</td>
<td>5.1401251</td>
<td>5.4416675</td>
<td>5.8931444</td>
</tr>
<tr>
<td><strong>Water Availability</strong></td>
<td>4.2794652</td>
<td>5.0747121</td>
<td>6.5360112</td>
<td>4.5920558</td>
</tr>
<tr>
<td><strong>Field Distance from Diversion</strong></td>
<td>1.2018021</td>
<td>1.2030769</td>
<td>1.1948040</td>
<td>1.2022178</td>
</tr>
</tbody>
</table>

**B8.2. Comments on statistical significance**

There are some shortcomings to the sample. The sample of irrigation systems is not balanced across the institutional configurations, and this lack of balance is even more pronounced at the field-level. This helps explain why some of the confidence bands are as large as they are, especially for rotational delivery without sharing. Additionally, there are relatively few fields at the extreme head and tail-end of systems, which helps explain why the confidence bands become so large at the extreme ends of the x-axis. That said, although statistical significance is a crucial guide for assessing the precision of results, the consistency of the trends across years and different dependent variables are encouraging. Additionally, statistical significance does not equate to agricultural significance. When predicted NDVI lies, with 90% or 95% confidence, between 0.19 to 0.4 under one institutional
configuration and 0.39 to 0.6 in another, these are meaningful differences to farmers even if they are not statistically different estimates.

B9. Dealing with Endogeneity

Over time, irrigation systems adopt rules based on the feedback irrigators receive from past performance (Ostrom, 2014). It could therefore be argued that the effects I find for different rules in use actually reflect past irrigation performance and/or the factors shaping past irrigation performance, not the current rules. I address this concern in three ways. First, I explain the problem and address the endogeneity argument conceptually. Second, I describe the steps taken in data analysis to address whatever endogeneity may be present. Third, I discuss the contradictory endogeneity stories that could be present in the data.

Additionally, even if an irrigation system may select a set of rules based on the performance it has had in the recent past and generally has had for other reasons, it is still interesting and useful to know what the deeper features of that performance are, specifically the relationship between head and tail-enders and marginal productivity. If the causal link goes the other way, the fact that there is a significant relationship is interesting and deserves the chance to be explained causally. Put another way, if these configurations are considered different solution spaces or basins of attraction that require mutually reinforcing institutions, physical contexts, and social processes, then knowing the significant features of
those solution spaces or basins of attraction will be useful to efforts to adapt to climate change.

B9.1. The conceptual argument against endogeneity

Lam (1998) covers the problem of endogeneity thoroughly on page 51, and I quote him at length. He begins by presenting the argument that “FIMS [Farmer Managed Irrigation Systems] that did not attain high levels of performance would have either died out, or had to learn from more successful FIMS how to craft more effective rules to improve their performance.” That is, the institutional arrangements of self-governing irrigation systems he observes in Nepal are products of Darwinian selection based on irrigation performance, and therefore the rules in use are endogenous. In response, he states:

While it would be reasonable to believe that a selection process is at work to a certain extent, the magnitude of the effect of such a process should not be overstated. As argued by political economics (North, 1990; E. Ostrom, 1990), while surviving institution arrangements are not necessarily effective, ineffective institutional arrangements could persist for a long period of time. On the one hand, an institutional arrangement is likely to give rise to vested interests with incentives to maintain the status quo arrangement (Knight, 1992). ... On the other hand, one should not assume that farmers in less effective FIMS would necessarily be able to learn from farmers in more effective systems in crafting effective rules. Institutional development is path-dependent (North, 1990; E. Ostrom, 1990; Blomquist, 1992). The kinds of change that are conceivable and practically possible are frequently determined by the status quo condition.

So, while feedbacks do occur, they do so slowly and may not actually generate aggregate net improvements; changes can occur which increase inequality and
which promote particular interests over others.\textsuperscript{2} And while certain factors and outcomes may make some rules in use more likely, they do not prescribe them by necessity nor negate the effects of the rules.\textsuperscript{3} Although these farmers are competing in a market context, provided that they can maintain economic viability, differential outcomes may not produce the degree of selection pressure scholars might think.

A crucial factor mitigating concerns about endogeneity in the SLV that the irrigation systems are very old, all being founded over 100 years ago. Their bylaws and norms have been established for many decades and it is costly to make changes, especially in a single season. Most farmers interviewed were able to describe their shortage sharing and delivery rules in great detail and without reflection, indicating that they had grown quite accustomed to the operations of the system over a long period of time. Many also had complaints about the rules, indicating that they viewed the rules as important for determining irrigation performance and not perfectly adapted.

\textit{B9.2. Accounting for endogeneity in the analysis}

While there is undoubtedly some institutional adaptation over time, provided that I account for the major factors that might shape rule selection in my regressions, I can be confident in my results. Table B.6 shows the distribution of

\textsuperscript{2} See Cody et al. (2015) for an in-depth discussion of the path-dependent nature of institutional change using the groundwater commons in the SLV as an example.

\textsuperscript{3} While on a very different time scale, the fact that the shape of a fish’s fin has been selected for swimming efficiency does not imply that different efficiencies measured across variations in fin shape are merely measurements of previous swimming efficiencies and ecological contexts.
some key variables that could shape performance and rule adoption. I pay special attention to performance, because this is the greatest threat to my regression results. To account for any endogeneity in my final regressions, I include the historical average percentage of the irrigation system’s acreage irrigated from 1984-2015 as well as water right priority. These variables could influence the adoption of shortage mitigating rules, so the inclusion of these variables reduces the chance that the variation introduced by this feedback is being absorbed by the rules in use. As another hedge against endogeneity, I use multiple years in my analysis to assess the effects of the institutional configurations in 2013. Interviews with irrigators make me confident that I can assume that over the short term (1-5 years) these institutional configurations are essentially stable, so that 2011, 2012, and 2014 have the same shortage sharing and delivery rules as those assessed in 2013. Importantly, there is no conceptual way that 2013 or 2014 performance could influence the rules used in 2013.

**B9.3. Contradictory endogeneity stories in the data**

Finally, if the effects I find for the variables of interest are in the opposite direction from what would be expected if the signal were endogenous, I can be further assured that endogeneity is not influencing my results. In my case, I expect shortage sharing and rotation to improve outcomes, whereas if the signal were endogenous, the observed effects of these rules would be negative. That is, worse performance should be associated with the adoption of these rules if these rules are
adopted to mitigate poor performance. However, an alternative endogeneity story posits that stronger performance leads to the adoption of these rules, because higher economic productivity facilitates collective action. Overall, the results do not support either endogeneity story. The results show that systems with simultaneous delivery and no shortage sharing are strong performers. This implies that the only endogeneity story that could be operating is that poor performance leads to the adoption of institutions for shortage mitigation: having strong performance, these systems had no need to adopt rules that adapt operations to shortage. However, systems that have adopted both shortage sharing and rotation also have strong performance; in this case, the only endogeneity story that could be operating is that strong performance creates the capital necessary to organize collective action. These two examples from the data falsify each other. So, while it is possible that both endogeneity stories are playing out with different strengths on different irrigation systems, the parsimonious interpretation is that endogeneity is not behind the results.

**Table B.6.** Key variables that may influence the selection of particular institutional configurations. Descriptive statistics given here are at the level of the irrigation system, not fields. There is an added category, Sole User, which indicates an irrigation system owned by one person. This category serves as a counterfactual to systems that must engage in collective action to achieve irrigation.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>SOLE (7, 11.7%)</td>
<td>Average Acreage: 619 Average Field</td>
<td>Percent Maximum Diversion: 44.5%</td>
<td>Water Right Percentile: 25.8</td>
<td>Acreage w/ Wells: 10.1% Acreage w/</td>
<td>Incorporated: 14.3% Monitoring: NA</td>
<td>Grass Pasture: 78.9% Alfalfa: 10.3</td>
<td>Acequia: 28.6% Average Users: 1.0</td>
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<td></td>
<td>Distance:</td>
<td>Percent Irrigated:</td>
<td>Catchment Area:</td>
<td>Sprinklers:</td>
<td>Allocate on Water Rights or Shares:</td>
<td>Acres per User:</td>
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<tr>
<td>--------</td>
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<td>----------------</td>
<td>------------</td>
<td>-------------------------------------</td>
<td>-----------------</td>
<td></td>
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<tr>
<td>SDNS (6, 10%)</td>
<td>1.657km</td>
<td>57.9%</td>
<td>224,090 Reservoir Access: 42.9%</td>
<td>4.3%</td>
<td>NA</td>
<td>619</td>
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<tr>
<td>SDS (11, 18.3%)</td>
<td>8.888km</td>
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<td>441,630 Reservoir Access: 50.0%</td>
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<td>RNS (8, 13.3%)</td>
<td>8.944km</td>
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<td>445,700 Reservoir Access: 56.4%</td>
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<td>RS (28, 46.7%)</td>
<td>8.202</td>
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<td>82,381 Reservoir Access: 61.7%</td>
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<td>ALL (60, 100%)</td>
<td>5.754km</td>
<td>61.2%</td>
<td>313,260 Reservoir Access: 61.7%</td>
<td>34.8%</td>
<td>100%</td>
<td>302</td>
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</table>
B10. Survey Questions and Available Responses Used in Analysis

*Is your water use association incorporated?*
Yes
No
In Process

*What is the current size of your association as measured in:*
Acres
Members

*Does your association have access to a surface reservoir?*
Yes
No

*Please mark whether the amount of water a member in your association can use is proportional to any of the following:*
The amount of land users own
The amount of water users have contributed
The amount of labor users are required to contribute
The amount of financial contributions users are required to make
Shares owned
Not proportional to anything
Other

*Within your association, is water normally distributed by turns along a rotation, or to everyone at once in proportion to their rights?*
Rotational
Proportional
Explanation

*Does this change when you have less than full flow?*
Yes
No
Explanation

*How is compliance with water use rules monitored and enforced (check all that apply)?*
No monitoring
Self-monitored by association members
Monitored by members
Monitored by Mayor Domo
Monitored by ditch rider
Monitored by water commissioner
Monitored by others
Do any formal or informal agreements among members of your association involve changing water allocations between them in times of drought and water scarcity?
Yes, Formal
Yes, Informal
No

What process, if any, exists for members to exchange water or land within your association?
OPEN ENDED RESPONSE

Please describe any scarcity arrangements, how frequently they are invoked, and any changes to irrigation or cultivation practices required during scarcity:
OPEN ENDED RESPONSE

For each threat identified, evaluate the extent to which that threat is problematic for your association, rating this from 1-5 (5 = very problematic, 1 = not problematic)
Poor quality infrastructure (1-5)
Poor quality soils (1-5)
APPENDIX B BIBLIOGRAPHY


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SUPPORTING INFORMATION FOR CHAPTER 4

C1. Tables and Figures Referenced in the Main Text

Table C.1. Variable measurement methods.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Measurement Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acequia</td>
<td>Systems founded before 1880 carrying a Spanish name were coded as 1.</td>
</tr>
<tr>
<td>Ditch Type</td>
<td>Systems were categorized by whether they were Acequias and then by geographic location.</td>
</tr>
<tr>
<td>Monitoring Agent</td>
<td>Systems reporting that they have a dedicated monitoring agent, either a “ditch rider” or “mayordomo” were coded as 1.</td>
</tr>
<tr>
<td>Days of Water Available Less than Normal</td>
<td>The reported number of days of normal water availability were subtracted from the reported number of days water was available in 2012.</td>
</tr>
<tr>
<td>Days Water is Normally Available</td>
<td>The reported number of days of normal water availability were reported.</td>
</tr>
<tr>
<td>Rotation in Scarcity</td>
<td>Systems reporting rotating water delivery in shortage were coded as 1.</td>
</tr>
<tr>
<td>Normally Rotate</td>
<td>Systems reporting rotating water delivery normally were coded as 1.</td>
</tr>
<tr>
<td>Labor Required</td>
<td>Systems reporting requiring labor to be delivered water were coded as 1.</td>
</tr>
<tr>
<td>Inter-System Sharing Arrangements</td>
<td>Systems reporting ongoing sharing arrangements with other irrigation systems were coded as 1.</td>
</tr>
<tr>
<td>Groundwater Wells</td>
<td>Systems reporting the use of groundwater wells were coded as 1.</td>
</tr>
<tr>
<td>Vegetable Gardens Present</td>
<td>Systems reporting vegetable gardens were coded as 1.</td>
</tr>
<tr>
<td>Long Lots Present</td>
<td>Systems determined through inspection of satellite imagery to contain long lots were coded as 1.</td>
</tr>
<tr>
<td>Change Allocations in Scarcity</td>
<td>Systems reporting changing water allocations in shortage were coded as 1.</td>
</tr>
<tr>
<td>Percent Hispanic</td>
<td>Using GIS data from the Census, the percentage of the population within the irrigation system reporting Hispanic heritage was calculated.</td>
</tr>
<tr>
<td>Water Not Allocated by Private Rights</td>
<td>Systems reporting that water is not allocated by private rights were coded as 1.</td>
</tr>
<tr>
<td>Dependency Ratio</td>
<td>Using GIS data from the Census, the percentage of the population within the irrigation system under 10 and 65 and over was calculated.</td>
</tr>
<tr>
<td>Hold Annual Meeting</td>
<td>Systems reporting an annual meeting of the users were coded as 1.</td>
</tr>
<tr>
<td>Percent Renters</td>
<td>Using GIS data from the Census, the percentage of the population within the irrigation system renting their home was calculated.</td>
</tr>
</tbody>
</table>
Percent Hydric Soils Using GIS data from the NRCS, the percentage of a ditch system with hydric soils was calculated.

Average Farm Acreage Using GIS data and the number of irrigators reported, the per capita acreage was calculated.

System Acreage Using GIS data, the area susceptible to irrigation by a given system was calculated.

Sprinkler Irrigation Systems reporting any sprinkler irrigation were coded as 1.

Bylaws Present Systems reporting bylaws were coded as 1.

US State Systems in New Mexico (Taos) coded as 1.

Per Capita Voting Systems voting on a per capita basis coded as 1.

Frequency of Water Use Violations Surveys revealed that water use violations occurred at one of five frequencies: Never, Less than Once Per Year, Once Per Year, More than Once Per Year, and Often.

2011-2014 Average System Average NDVI in July Monthly NDVI rasters were accessed from Google Earth Engine using Landsat images from USGS. Each month from May 2011 through August 2014 was evaluated for cloud cover and NDVI intensity. July was deemed the highest quality across all four years and four NDVI rasters were downloaded and loaded into ArcGIS 10.5. In conjunction with rasters of each unique ditch system, the average NDVI value for each system in July of each year of the study period was calculated using Zonal Statistics after setting values less than 0.3 (unirrigated) to 0.

2011-2014 Average System Spatial Standard Deviation of NDVI in July Monthly NDVI rasters were accessed from Google Earth Engine using Landsat images from USGS. Each month from May 2011 through August 2014 was evaluated for cloud cover and NDVI intensity. July was deemed the highest quality across all four years and four NDVI rasters were downloaded and loaded into ArcGIS 10.5. In conjunction with rasters of each unique ditch system, the spatial standard deviation of NDVI for each system in July of each year of the study period was calculated using Zonal Statistics after setting values less than 0.3 (unirrigated) to 0.

**Table C.2.** Poisson regression outputs from Equation 1 investigating the influence of Ditch Type on the number of system features from Table 4.4. Anglo is the reference level. Taos is excluded from column (2) as a robustness check. Significance is: * p< 0.1; ** p<0.05; *** p<0.01.

<table>
<thead>
<tr>
<th>Count of 13 Features Conducive to Collective Action</th>
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</thead>
<tbody>
<tr>
<td>CONEJOS</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>COSTILLA</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>TAOS</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PERRENT</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PERHISP</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>
Table C.3. Poisson regression outputs from Equation 1 investigating the influence of Ditch Type on the number of system features from Table 4.4. Anglo is the reference level. Taos and Costilla are grouped together, while compared to Appendix Table C.2 the second column is dropped because they are identical regressions. Significance is: * p<0.1; ** p<0.05; *** p<0.01.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>Z Value</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
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<td>(0.1736)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAOS&amp;COSTILLA</td>
<td>0.7656***</td>
<td>(0.1770)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERRENT</td>
<td>0.0053</td>
<td>(0.0051)</td>
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<td>PERHISP</td>
<td>0.0019</td>
<td>(0.0028)</td>
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<tr>
<td>PERHYD</td>
<td>-0.0004</td>
<td>(0.0035)</td>
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<td>(0.0003)</td>
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<td>(0.0048)</td>
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<td>log(WATNORM)</td>
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<td>(0.0879)</td>
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<tr>
<td>log(ACRES)</td>
<td>0.0146</td>
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</tr>
</tbody>
</table>

Observations | 69 | 51
Log Likelihood | -138.8517 | -98.5013
Akaike Inf. Crit. | 299.7034 | 217.0026
Table C.4. The role of Ditch Type on the adoption of the individual features given in Table 4 of Chapter 4. Anglo is the reference level. Taos is excluded from the first four columns due to lack of variation in the DV. Two logit regressions failed due to the data perfectly predicting the DV (gardens, long lots) and are excluded. In the first four columns, Taos has no variability in the DV and is also excluded. Significance is: *p<0.1; **p<0.05; ***p<0.01.
Table C.5. The role of Ditch Type on the adoption of the individual features given in Table 4.4. Anglo is the reference level. Taos is grouped with Costilla. Two logit regressions failed due to the data perfectly predicting the DV (gardens, long lots) and are excluded, as in Table C.4. Four columns are also excluded because their results are identical to the first four columns in Table C.4, where Taos is excluded. Significance is: * p< 0.1; ** p<0.05; *** p<0.01.

<table>
<thead>
<tr>
<th>Ditch Type</th>
<th>Allocation Changes</th>
<th>All Flood Voting</th>
<th>Per Capita Voting</th>
<th>Labor Required</th>
<th>Normally Rotate</th>
<th>Water Not Private</th>
<th>Inter System Sharing</th>
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<td>Obs.</td>
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</tbody>
</table>
Table C.6. Full table of regressions testing H2, H3, and H4 using Equation 2. Anglo is the reference group. Taos and Costilla are combined due to their contemporary and historical cultural and legal similarities. *p<0.1; **p<0.05; ***p<0.01

<table>
<thead>
<tr>
<th>Dependent variable:</th>
<th>Water Misuse Once per Year or More</th>
<th>Mean NDVI</th>
<th>Mean Spatial Standard Deviation of NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>logistic (1)</td>
<td>OLS (2)</td>
<td>OLS (3)</td>
</tr>
<tr>
<td>CONEJOS</td>
<td>-3.4716** (1.7121)</td>
<td>0.7222 (0.5011)</td>
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<td>0.1365 (0.4314)</td>
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<td>ROTSRC</td>
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<td>2.1941</td>
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</table>
Table C.7. Full table of regressions testing H2, H3, and H4 using Equation 2. Anglo is the reference group. All acequias are combined into a single aggregation. *p<0.1; **p<0.05; ***p<0.01

<table>
<thead>
<tr>
<th>Dependent variable:</th>
<th>Water Misuse Once per Year or More</th>
<th>Mean NDVI</th>
<th>Mean Spatial Standard Deviation of NDVI</th>
</tr>
</thead>
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<td>OLS (2)</td>
<td>OLS (3)</td>
</tr>
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<td></td>
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<td>Standard Error</td>
<td>p-value</td>
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<td>------------------------</td>
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<td>CONST.</td>
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<td>0.9863</td>
<td>-2.6474***</td>
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</table>

**BIC:** 125.3685 | 232.6464 | 204.6486

**AIC:** 91.4283 | 196.4436 | 168.4457

**Observations:** 71 | 71 | 71

**R²:** 0.3981 | 0.5942

**Adjusted R²:** 0.2476 | 0.4928

**Log Likelihood:** -30.7141

**Residual Std. Error (df = 56):** 0.8674 | 0.7122

**F Statistic (df = 14; 56):** 2.6451*** | 5.8573***
Figure C.1. Predicted probability of water misuse once or more per year on Anglo irrigation systems and *acequias* depending on whether or not a monitoring agent is present.

**Norms Moderate Effect of Monitoring on Probability of Rule Violation Frequency**

[Graph showing the predicted probability of water misuse once or more per year on Anglo irrigation systems and *acequias* depending on whether or not a monitoring agent is present.]
Figure C.2. Predicted mean NDVI for Anglo irrigation systems and *acequias* depending on whether or not a monitoring agent is present.

**Norms Moderate Effect of Monitoring Agent on NDVI (2011-2014)**

![Graph showing predicted mean NDVI for Anglo irrigation systems and acequias depending on whether or not a monitoring agent is present.](image)

- **x-axis (Acequia)**: 0 to 1
- **y-axis (Predicted NDVI, scaled)**: -1.5 to 0.5
- **Legend**:
  - Monitoring Agent: 0 (Blue line and dots), 1 (Red line and dots)

The graph illustrates a significant difference in predicted NDVI between systems with and without a monitoring agent.
Figure C.3. Predicted standard deviation of NDVI for Anglo irrigation systems and acequias depending on whether or not a monitoring agent is present.

**Norms Moderate Effect of Monitoring Agent on Standard Deviation of NDVI (2011-2014)**
Figure C.4. Predicted probability of water misuse once or more per year on Anglo irrigation systems and Conejos *acequias* vs. *acequias* from Costilla and Taos depending on whether or not a monitoring agent is present.

**Norms Moderate Effect of Monitoring on Probability of Rule Violation Frequency**

![Graph showing the effect of monitoring on the probability of rule violation frequency. The graph compares the predicted probability of water misuse once or more per year on Anglo irrigation systems and Conejos *acequias* vs. *acequias* from Costilla and Taos depending on whether or not a monitoring agent is present. The x-axis represents the ditch type, and the y-axis represents the predicted probability of water misuse. The graph shows a clear decrease in predicted probability with the presence of a monitoring agent.]
Figure C.5. Predicted mean NDVI for Anglo irrigation systems and Conejos acequias vs. acequias from Costilla and Taos depending on whether or not a monitoring agent is present.

**Norms Moderate Effect of Monitoring Agent on NDVI (2011-2014)**

<table>
<thead>
<tr>
<th>Monitoring Agent</th>
<th>NDVI (scaled)</th>
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</thead>
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<tr>
<td>0</td>
<td>-1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.5</td>
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</tbody>
</table>

Ditch_Type_TC_AC

291
Figure C.6. Predicted standard deviation of NDVI for Anglo irrigation systems and Conejos acequias vs. acequias from Costilla and Taos depending on whether or not a monitoring agent is present.

Norms Moderate Effect of Monitoring Agent on Standard Deviation of NDVI (2011-2014)

C2. Study Period as Analog to Climate Change Conditions

Climate change is expected to bring lower levels of snowpack to many mountains around the world (FAO, 2012; Gleick, 2003). As Figure C.7 shows, the Upper Rio Grande Basin received lower than average snowpack during the study period, making the study period an appropriate test of irrigation system performance under expected climate change conditions.
Figure C.7. Snowpack in the SLV from 2011-2014, showing below normal volume, earlier peak, and earlier melt (NRCS, n.d.).

C3. Extended History of Hispanics and Anglo-Americans in the URGB

Acequias, a form of farmer owned and operated gravity driven irrigation, developed first in the Middle East and North Africa and were brought to the Iberian Peninsula during the Umayyad Caliphate. This form of irrigation was subsequently brought to the Americas by the Spanish and has persisted in what is now the United States along the Rio Grande since the early 1600s. As the Spanish moved Northward towards the headwaters of the Rio Grande, reaching what is now the San Luis Valley (SLV) just before 1850, acequias faced pressure to sustain human populations primarily through small-scale subsistence agriculture, having limited
access to markets to sell their crops and obtain technologies such as metal tools and machinery. The Spanish irrigators, native Puebloans, and other native groups periodically traded, raided, and intermarried. Labor was also scarce in the more remote reaches of the Spanish dominion, and so whole families were involved in the production process. The Catholic Church incorporated itself and religious sacrament into the irrigation practices of the Spanish, resulting in the conflation of good behavior around irrigation with piety, generating even more incentives for cooperation.

By Spanish law, water and land were owned largely in common, and it was therefore difficult for any one person or family to monopolize resources. Furthermore, although there was social hierarchy among members of the community, acequías operated on a “one land owner, one vote” system, so that even the poorest among them had equal bargaining power with the wealthiest when it came to making decisions about water use. There were also important equalizing features within the community, including the inheritance of land by all sons rather than the eldest son. With a limited market and little oversight from the major power base in Santa Fe, Spanish irrigators relied heavily on collective action, a sense of duty, and sustainable land management to build, maintain, and operate the irrigation works which gave life to their crops, livestock, and families. Acequías therefore adopted and refined a set of institutional and technological adaptations to aridity and community subsistence and defense, as opposed to individualistic
market competition, which were passed through generations of farmers on Hispanic irrigation systems.

Anglo-American expansion across the North American West began in earnest with the end of the American Civil War. Enabled by the Homestead Act of 1862, any man who had not taken up arms against the US government, was 21 years of age, and brought land under cultivation (or “improved” it, in the language of the law) and then maintained his residence there for five years would be allocated up to 160 acres of land (i.e. a “quarter section” of the Public Land Survey System). The US Military expelled Native Americans from the SLV in the 1870s. When the Anglos arrived, they brought with them their tools, crops, livestock, and cultural norms of self-reliance, an orientation towards market competition, and laws of private property in land and water. It was therefore relatively easy for individuals to monopolize resources, and voting power on the irrigation system was often proportional to the water rights owned. Bargaining power grew increasingly unequal between individuals as fortunes diverged and consolidated as the eldest son inherited his father’s land.

Upon arriving, Anglos found that Hispanic *acequias* had already occupied much of the land in the southern portion of the SLV, especially in what are now Costilla and Conejos counties, with some in Rio Grande County. The PLSS disrupted the landholdings of the Spanish in the area except for in Taos and Costilla Counties. Water was *de jure* privatized in all counties, though *de facto* common property persisted in Taos. Additionally, the *ejido* uplands of the *acequia*
communities, used to gather timber, medicinal plants, hunting and grazing, were turned into either private or government property. Although there were some attempts to dislodge the Hispanics by Homesteaders, the Treaty of Guadalupe Hidalgo kept the US Military from assisting the Homesteaders in their efforts, and the Hispanics were largely able to maintain their landholdings despite legal subjugation and extralegal harassment.

As the railroads made their way into the SLV around 1880, the population of Anglos and access to markets expanded dramatically. Relative newcomers to aridity, it become clear to the Anglos early on that irrigation would be necessary to sustain crops, and scale would be necessary to reap profitable harvests. Thus, land speculation became commonplace, with investors from New York, London, and elsewhere making large investments in irrigation infrastructure and mechanized farming tools. Most of those investments would fail, and the large scale commercial systems and methods of farming would eventually fall into the hands of the people that used them. Recognizing the importance of collective action for irrigation and skeptical of external control of their means of production, these farmers became active in self-governance of their irrigation systems and resources, resisting government and corporate interest in their land and water. Over time, these irrigators adopted and refined a set of institutional and technological adaptations to aridity and individualistic market competition, as opposed to community subsistence, which were passed through generations of farmers on Anglo irrigation systems.
C4. Survey Recruitment, Instrument Development, and Administration

The survey instrument was developed in concert with a research team conducting similar work in Kenya (McCord et al., 2015) and with stakeholders in the Upper Rio Grande Basin. Systems targeted for surveying were identified using data from the DNR website and previous research in Taos (Cox, 2010). To stratify the sample, systems were grouped based on their water right priority rank (above/below the median ranking in their watershed, not relevant for Taos), watershed (one of nine), stream location (above/below the median ranking in their watershed), well usage (1/0, not relevant for Taos), acreage (above/below the median ranking in the basin), and acequia status (1/0, not relevant for Taos). A random number was then assigned to every system and samples were drawn in descending order from each watershed.

The survey was conducted in Colorado over two, two-week sampling bouts in May and June of 2013. Taos was surveyed in September 2013. The instrument was developed in concert with community leaders to address questions they had as well as make theoretical abstractions more meaningful for irrigators. Surveys were administered face to face at a location of the interviewee’s choosing by one to three researchers at a time, with one researcher leading the questioning and writing down answers, and in Colorado the others taking notes and confirming accurate recording of responses. Each night after samples were collected in Colorado the research groups came together to align their understanding of the responses and to identify where improvements to the instrument and its administration could be
made. To ensure that questions were being asked the same way by different researchers, the groups of researchers were mixed each day, if not multiple times each day, and discrepancies were quickly and retroactively addressed. In Taos, one survey administrator who also administered surveys in Colorado took survey responses. The average administration time was approximately 60 minutes. The surveys were conducted in English.

C5. Software and Data Analysis

Data were processed in R version 3.4.3 and ArcGIS 10.5 unless otherwise indicated. All analyses were run in R version 3.4.3 unless otherwise indicated. Logistic and Poisson models were estimated using the glm function in the base stats package. Tobit models were estimated using censReg (version 0.5-26) (Henningsen, 2017). Regression tables were generated using stargazer (version 5.2.1) (Hlavac, 2018). Spatial error models were fit using spdep (version 0.7-4) (Bivand & Piras, 2015) and McSpatial (version 2.0) (McMillen, 2013). Effects plots were generated using effects (version 4.0-0) (Fox, 2003).

C6. Identification of Irrigation System Features Engendering Cooperation

Especially important for the features which may engender cooperation are considerations of the groundwater table and return flows. The groundwater table is very important because it supports water supplies that many irrigators rely on, including seeps, springs, and sub-irrigation (where crops are able to obtain water
from the water table directly without surface irrigation). A high groundwater table also crucially provides water to surface streams, whereas groundwater withdrawals deplete surface flows due to hydrologic connectivity, impacting all farmers using surface water. Return flows are also important because they recharge the groundwater table, but more importantly they provide direct surface runoff from fields which is then utilized by subsequent irrigators. In this way, water is “reused” by multiple irrigators on an irrigation system. A common phrase heard among water users is, “return flow makes the system go.” The adoption of groundwater wells or sprinklers, and the subsequent reduction of the groundwater table and return flows, can be seen as a competitive and individualistic behavior; it increases the consumptive use of water by one farmer, but reduces water availability to the rest of the irrigation system and watershed.

C7. On the Distribution of Monitoring Agents

There is a relatively equal distribution of systems in the study area on which a monitoring agent is present; only Taos acequias are significantly more likely to have a monitoring agent (Figure C.28). This may be because a monitoring agent is legally required for acequias in New Mexico. However, the average number of irrigators per system in Taos is 74, so large that most systems would almost certainly utilize a monitoring agent, regardless of the law. Only two acequias in Taos have fewer than 20 irrigators, the smallest having 13. Of the systems in the sample without a monitoring agent, the system with the most irrigators is an
acequia in Costilla County, with nine. Whether Anglo or Hispanic, the average number of irrigators on systems without a monitoring agent rounds to four. Therefore, the use of a monitoring agent appears to be more a function of the number of irrigators than state law.

**C8. Raw Data on Monitoring and Water Use Violations**

The raw data substantiate the above qualitative data. Twenty irrigation systems (28%) have no monitoring agent, so these systems rely much more on social processes rather than enforced rules and therefore provide greater insight into norms. Of the eight Anglo systems without a monitoring agent, seven (88%) report water use violations, as compared to just five (42%) of the 12 acequias without monitoring agents. Only five of the 20 systems without a monitoring agent do not report some form of irrigator-on-irrigator monitoring, which lacks the rule enforcement powers vested in the monitoring agent and relies on peer enforcement of norms. Three of these five are acequias, one of which reports no water use violations, while the rest of the five without irrigator-on-irrigator monitoring report water use violations. Of the 15 systems that do have some form of irrigator-on-irrigator monitoring, nine are acequias and three (33%) of those report violations, compared to five of the six (83%) Anglo systems with irrigator-on-irrigator monitoring reporting water use violations. It is this last breakdown that is most telling; even when others are watching, Anglo systems are two and a half times
more likely to report water misuse. Overall, only one Anglo system without a monitoring agent does not report water misuse.

C9. Summary of Results

Results show that where cooperative norms and rules are congruent, norms can accomplish similar if not identical rule compliance as a monitoring agent with the authority to punish. Monitoring agents enforcing rules congruent with cooperative norms also appear to optimize water delivery for equal crop production at the expense of higher average crop production. Where competitive norms are internalized, a monitoring agent is associated with lower rule violations and higher average crop production with no differences in the equality of crop production, suggesting the effect of the monitoring agent on irrigation is to reduce water waste. However, where enforced rules are not congruent with cooperative norms, monitoring agents are associated with increased rule violations and worse average crop production with no improvements to the equality of crop production. This suggests that monitoring agents in this context are not able to effectively optimize water delivery in accordance with private water rights and these systems may therefore be wasting water.
C10. Variable Summaries

Figure C.8. Deviation from number of days water normally available in 2012.

![Sensitivity to Drought](image)

Ditch Type:
- Anglo
- OtherColorado
- Costilla
- Taos

Number of Days Water Unavailable in 2012 Drought Compared to Normal
Figure C.9. Number of days water is normally available.
Figure C.10. Total acreage of irrigation systems.
Figure C.11. Average amount of land available to each farmer.
Figure C.12. Dependency Ratio.

Dependency Ratio

Percent of Population Aged Under 10 and Over 65

Ditch Type

Anglo OtherColorado Costilla Taos
Figure C.13. Percent of the ditch system with hydric soils.
Figure C.14. Percentage of people living within the irrigation system which identify as Hispanic.

![Box plot showing the percentage of the population identifying as Hispanic across different ditch types](image)

- **Anglo**
- **OtherColorado**
- **Costilla**
- **Taos**

The box plots show the distribution of the percentage of the population identifying as Hispanic for each ditch type. The median values are indicated by the black lines within the boxes.
Figure C.15. Percentage of people living within the irrigation system who rent their dwelling.
Figure C.16. Distribution of irrigation systems utilizing long-lots.

### Long Lots

<table>
<thead>
<tr>
<th>Ditch Type</th>
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<tbody>
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<tr>
<td>OtherColorado</td>
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</tr>
<tr>
<td>Costilla</td>
<td>0.2</td>
</tr>
<tr>
<td>Taos</td>
<td>0.0</td>
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</table>
Figure C.17. Distribution of systems growing vegetable gardens.
Figure C.18. Distribution of systems requiring labor for membership.
Figure C.19. Distribution of systems with written bylaws.
Figure C.20. Distribution of systems allocating water based on private rights.

Water Allocated by Private Rights

Ditch Type

Absence = 0, Presence = 1
Figure C.21. Distribution of systems normally rotating water.
Figure C.22. Distribution of systems with ongoing inter-system sharing agreements.

**Ongoing Inter–System Sharing Agreements**

- Anglo
- OtherColorado
- Costilla
- Taos

Ditch Type

Absence = 0, Presence = 1

Ongoing Inter-system sharing agreements.
Figure C.23. Distribution of systems voting on a per capita basis.

Per Capita Voting

Absence = 0, Presence = 1

Anglo OtherColorado Costilla Taos

Ditch Type
Figure C.24. Distribution of systems using only flood irrigation.
Figure C.25. Distribution of systems changing water allocations in the shortage.
Figure C.26. Distribution of systems holding an annual meeting.

**Hold an Annual Meeting**

Absence = 0, Presence = 1

- Anglo
- Other Colorado
- Costilla
- Taos

Ditch Type
Figure C.27. Distribution of systems with high capacity groundwater wells.
Figure C.28. Distribution of systems appointing a monitoring agent.
Figure C.29. Distribution of systems rotating water delivery in shortage.

Rotates Water Delivery in Scarcity

Absence = 0, Presence = 1

Anglo OtherColorado Costilla Taos

Ditch Type
Figure C.30. Distribution of frequency of water use violations.
Figure C.31. Distribution of water use violations occurring more than annually.
Figure C.32. Distribution of water use violations occurring once per year or more.
Figure C.33. Distribution of water use violations occurring at all.

Illicit Water Use Occurs

Absence = 0, Presence = 1

Ditch Type

Anglo OtherColorado Costilla Taos

0 0.2 0.4 0.6 0.8 1.0
Figure C.34. Correlation matrix (Pearson’s) showing the strength and significance \((p < 0.05)\) of the correlations between the 13 features conducive for collective action presented in the main text in Table 4 of Chapter 4.
APPENDIX C BIBLIOGRAPHY


