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Paper Water, Wet Water, and the Recognition of Indigenous Property Rights*

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Abstract

Restoring natural resource access for Indigenous groups has become a recent policy focus. We combine satellite data and robust difference-in-difference methods to estimate the causal effect of Native American water right settlements on land and water use on reservations in the western United States over 1974–2012. We find that settlements increase cultivated agricultural land use (crops and hay/pasture) by 8.7%. Our estimates of tribal water use indicate that, even after accounting for water leased off reservation, many tribes are utilizing only a fraction of their entitlements, forgoing as much as $938M–$1.8B in revenue. We provide evidence suggesting that this gap is driven, in part, by land tenure constraints and a lack of irrigation infrastructure.

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1 Introduction

Throughout the world and well into the 20th century, natural resources traditionally governed by Indigenous people were enclosed, allocated, or otherwise appropriated as part of settlement and colonization. Preexisting Indigenous property rights (formal and informal) were generally ignored or extinguished in the process, often without compensation. In the United States, the loss of natural resources ranging from land and water to salmon and bison has been suggested as a key reason why many Indigenous communities fare worse on a variety of margins than surrounding non-Indigenous populations (Carmody and Taylor, 2016; Parker et al., 2016; Feir et al., 2019; Farrell et al., 2021), as many Indigenous groups remain highly reliant on natural resource extraction for their livelihoods, including subsistence and for-market agriculture, fishing, and hunting.

Globally and in the United States, restoring natural resource access to historically marginalized Indigenous groups has become a legal and policy focus. The 1974 Boldt Decision (United States v. Washington) allocated substantial fishing rights to tribes in Washington State and the 2020 McGirt ruling (McGirt v. Oklahoma) led to roughly half of the land in Oklahoma coming under the jurisdiction of the Muscogee (Creek) Nation.[1] Internationally, restoration of natural resource rights has occurred for Australian aboriginal land and water (Mabo and Others v. Queensland (no. 2) 1992 HCA 23; Native Title Act 1993); Chilean Indigenous land and water (Heise, 2001; Tomaselli, 2012); and New Zealand Maori land (the Ngai Tahu and Waikato-Tainui settlements) and customary water and fishing claims (Gibbs, 2000; Te Aho, 2010).

While property rights to natural resources can increase economic value and improve ecological health (Libecap, 2007; Costello et al., 2008), causal analyses of the effects of Indigenous rights restoration have been limited. What studies have been undertaken have shown mixed results (Parker et al., 2016; Blackman et al., 2017; Robinson et al., 2017). In this paper, we estimate the effect of a large-scale attempt to recognize Indigenous rights to water. Specifically, we study the economic impacts of the allocation of formal property rights to water for tribal nations in the western United States, where water is a culturally and economically significant resource.

The recognition of formal Indigenous property rights to large volumes of scarce water across the American West has resulted from a U.S. Supreme Court ruling (Winters v. United States, 1908)

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[1] The full citations for these decisions are, respectively: United States v. Washington, 384 F. Supp. 312, aff'd, 520 F.2d 676 and McGirt v. Oklahoma, 140 S. Ct. 2452.

that granted tribes formal title to high-priority water rights based on historical treaties. This process required re-allocating water from existing users that were subsequently made junior to tribes. To date, settled "Winters rights" total 2.8 million acre-feet, enough water for the domestic use of 20 million southwest U.S. residents or approximately 1 million acres of irrigated agriculture. Within the Colorado River Basin, tribes have obtained entitlements totalling 20 percent of the river's annual flow (U.S. Bureau of Reclamation, 2018). The potential volume of unsettled tribal water rights that are currently being adjudicated could exceed 1.6 million acre-feet (Sanchez et al., 2020). Hence, measuring the implications of Winters settlements for land and water use is important not just for tribal policy and economic development, but for agricultural users, urban water suppliers, and policymakers across the western United States.

We study the effect of tribal water right settlements with a parcel-level difference-in-difference model using newly developed estimators robust to heterogeneity and staggered treatment timing (de Chaisemartin and d'Haultfoeuille, 2020; Callaway and Sant'Anna, 2021). Because historical administrative data on land use and social and economic outcomes are limited on reservations, we use satellite estimates of land use available starting in 1974 to detect the impact of settlements (Falcone, 2015). The duration of negotiations is plausibly exogenous, ranging from five to 50 years, allowing us to obtain a causal estimate of the effect of settlement on changes to agricultural land use relative to reservations that had begun but not yet completed the settlement process.

Our estimates show that after obtaining formal water rights, agricultural land use on reservations increased by up to 0.61 percentage points, which translates into a 8.7 percent increase relative to mean agricultural land use. Our results are robust across four separate difference-in-difference estimators and alternative measures of agricultural land use. We do not find increases in developed land use following settlement, consistent with agriculture being the primary use of water and the focus of Winters settlements (Brewer et al., 2008; Sanchez et al., 2020). After presenting our core estimates of the effect of Winters settlements on reservation land use, we explore the implications for tribal *water* use and provide some suggestive evidence regarding the factors that may explain the relatively modest effect of Winters settlements to date.

In a back-of-the-envelope exercise, we convert the land use estimates into water use and find that the estimated change is small compared to the overall water allocated by settlements. We collect data on environmental water use and off-reservation leasing for each tribe and combine these with our back-of-the-envelope estimates for agricultural and municipal use to estimate total reservation water use. The total volume of reservation water use is well below the entitlements obtained via Winters settlement on the majority of reservations.

Our water accounting estimates are consistent with previous findings conducted for a subset of Winters tribes (U.S. Bureau of Reclamation, 2018), and suggest that many tribes have not yet put their full allocation of “paper rights” into use. Even if there are no additional Winters adjudications, tribes that have previously secured their rights could potentially put an additional 1.1 to 2.6 million acre-feet of water to use annually — water entitlements now technically owned by tribes but currently diverted by off-reservation users. If this water is put into agricultural use or leased, we estimate that its value to tribes would range from $938 million to $1.8 billion annually.

We explore several explanations for the observed underutilization of Winters rights. Interviews, discussion, and data from U.S. Bureau of Reclamation (2018) suggest “significant issues” facing tribes including: the hesitancy of water development partners to invest due to sovereign immunity and land tenure issues, restrictions on the ability to voluntarily transfer or lease water, and a lack of ”monetary resources and/or technical expertise to independently maintain or rehabilitate major agricultural infrastructure” (U.S. Bureau of Reclamation, 2018). We explore the relative magnitude of these explanations for the lag in tribal utilization of water rights. We find evidence supporting U.S. Bureau of Reclamation’s claims, however this evidence is not conclusive. A lack of large-scale irrigation capital at the reservation level and constraints on land rights at the parcel level help explain some, but not all, of the difference between Winters entitlements and post-settlement water use.

We also discuss whether the unexplained shortfall can be attributed to alternative goals not captured by our estimated treatment effects, including changes in residential water supply, environmental uses, and option values. Ultimately, there is limited evidence to support these hypotheses. Hence, while restoring Indigenous water rights is an important step in terms of procedural justice, the effect in terms of delivering water to reservations or allowing tribes to benefit from leasing this water off-reservation has been limited.

2 Background

2.1 Securing Winters Rights

Surface water in the western United States is governed by the prior appropriation doctrine, which assigns water rights based on the chronological priority of the initial claim. This "first in time, first in right" system ensures the earliest (senior) appropriators access to water in all but the driest years, forcing juniors to curtail their usage first. States assigned the earliest appropriative rights to white settlers starting in the 1850s, and by the early-1900s, most basins were fully appropriated. Around the same time, the federal government relegated tribes to reservations established by tribe-specific reservation treaties.

While reservation treaties and successive federal policies established expectations that tribes would sustain themselves through agriculture, tribes' water supply needs were not considered when reservations were created (Carlson, 1981). States, which have the authority to allocate water within their borders, largely did not allocate water rights to tribes. Without enforceable water rights, water supplies on reservations became scarce and highly variable as nearby off-reservation water use by upstream and downstream right holders increased. Court documents filed by tribes describe the consequent depletion of reservation streams, springs, and aquifers. For example, the Ak-Chin, Jicarilla Apache, Tohono O'odham, and Hopi tribes sought legal protection when existing wells went dry and irrigation was abandoned due to off-reservation water use (of Water Resources, 2006; Ak Chin Indian Community v. United States , 1973).

A 1908 Supreme Court ruling (Winters v. United States, 1908) affirmed that while not explicitly mentioned, reservation treaties implicitly reserve water rights for tribes with a priority based on the date that the treaty was signed. The ruling did not provide quantified, legal water rights. Instead, it created a legal obligation for the federal government, as a trustee of tribal resources, to remedy its neglect in filing water claims on behalf of tribes. Thus, tribes have legal claims to high-priority water rights, referred to as Winters rights, but the rights themselves do not exist in a *de facto* sense until they are adjudicated (Sanchez et al., 2020).[2] A handful of tribes acquired Winters Rights via court decree in the first 50 years following the Supreme Court ruling. Subsequent

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[2] Winters Rights cannot be forfeited even if the tribe has never diverted or used the water, because they are "federally reserved." After adjudication, tribes enact water codes that standardize rules for approving, conditioning, and revoking water use permits on-reservation (Termyn, 2018). Typically, any individual (Indian or non-Indian) on a reservation can apply for water use permits, which are approved by a tribal water authority (Breckenridge, 2006).

Winters rights have been adjudicated through settlement agreements negotiated with neighboring water users, states, and the federal government.

The priority date for a tribe's Winters rights corresponds to the date of the tribe's reservation treaty, or "time immemorial" for tribes that never signed a reservation treaty. Because reservations were typically formed prior to the arrival of white settlers and subsequent development of state water claims, Winters rights are usually the highest priority rights in a basin. Figure A1 illustrates this by depicting the relative priority and magnitude of Winters rights for eleven different tribes using data on post-settlement rights held by tribes and off-reservation irrigation districts compiled by Sanchez (2022). The security of Winters rights is underscored by the fact that they tend to be "first in line" within the prior appropriation system and small relative to the total volume of water rights allocated in a basin. Together, these facts imply that only the most severe droughts would constrain the availability of Winters' rights for a tribe that is equipped to use them.

Sanchez et al. (2020) study the settlement process in depth, characterizing i) the factors that lead tribes to begin the adjudication process initially and ii) factors associated with differences in the length of the process and expected water rights entitlements. Consistent with economic expectations, tribes are more likely to begin the process of adjudication when they expect larger gains, e.g., reservations with more arable land and increasing water scarcity, measured by stream order and changes in precipitation. Importantly, once a reservation enters into the adjudication process, the speed with which settlement occurs is a function of factors that are largely exogenous to the reservations, such as the majority party in Congress and the number of off-reservation parties included in the adjudication. This is because settlements must ultimately be approved by Congress, which typically provides funding for infrastructure and economic development. We return to this discussion and its implications for identification in Section 3.2.2.

2.2 Putting Winters Rights to Use

In principle, Winters rights can be put to a variety of uses by tribes. In this paper, we focus primarily on agriculture. The prevalence of agriculture relative to other economic activities on reservations prior to water settlements, as well as existing farm infrastructure, suggests that changes to agricultural land use from a water settlement may occur more quickly than even more capital-intensive shifts toward non-agricultural development. Agriculture remains the dominant water use in our study area. Irrigated agriculture accounts for as much as 80% of total water use in the American West (Culp et al., 2014). Further, agriculture is the primary economic activity on 75% of reservation land (Mondou, 1998), and tribes across the West cite insufficient water for agriculture as a top concern (Singletary et al., 2016). This is underscored by the fact that a study coauthored between USBR and ten tribes throughout the Colorado River Basin found that nearly all water use on reservations is agricultural (U.S. Bureau of Reclamation, 2018).

Moreover, agricultural water use is often the explicit focus of Winters settlements. A 1963 Supreme Court ruling (Arizona v. California, 1963) clarified that because agriculture was the original purpose of a reservation, tribes have rights to enough water to cultivate every irrigable reservation acre, establishing what is known as the Practicably Irrigable Acreage (PIA) standard. Reservations can typically maximize their Winters claims under the PIA standard, leading to larger water entitlements and higher levels of federal funding (Sanchez et al., 2020).[3]

On-reservation water development faces dual challenges related to competing resource users and overlapping institutional failures. Western water law favors *beneficial use*, and holding title to a water right does not guarantee control of the resource. The nature of prior appropriation allows junior users to use senior (in this case, tribal) rights without compensation as long as the senior user lacks the ability to put their water rights to beneficial use. The upshot is that pre-existing institutional barriers that limit tribes' ability to build diversion infrastructure and install irrigation systems can prevent them from initially asserting their *de facto* ownership of their new rights.[4] Moreover, tribes are typically unable to receive compensation for off-reservation water use because Congressional approval is required for tribes to lease their rights, and many tribes are therefore not allowed to do so (Non-Intercourse Act, 25 U.S.C. §177, 1834). We return to these issues in Section 5.

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[3] Subsequent rulings allowed for broader interpretations of a reservation's "purpose" beyond agriculture. Gila V (2001) expanded the definition of a reservation's "purpose" to include non-agricultural water needs, and United States. v. Adair (1984) acknowledged that Winters rights could be claimed for non-consumptive uses, such as instream flow to maintain tribal fisheries and hunting grounds.

[4] Under western water law, failure to put a right to beneficial use can allow appropriation by junior users and, eventually, the right is forfeited due to "non-use." The federally reserved status of tribal rights means that they cannot be forfeited for non-use. Tribal governments themselves have expressed concerns over the need to bring water onto the reservation to establish a secure claim.

3 Data & Empirical Strategy

3.1 Data

A persistent challenge for conducting empirical research on reservations is the lack of fine-scale, longitudinal data. Previous analyses rely on the U.S. Census, which aggregates variables such as income and farm sales to the reservation level, only collects data for some reservations, and is largely only available from 1980 onward. We overcome these limitations by combining several data sources: i) fine-scale measures of land tenure and land use on reservations assembled by Dippel et al. (2020); ii) information on tribal water settlements compiled from adjudication filings, court records, and settlement texts by Sanchez et al. (2020); and iii) important, time-varying reservation characteristics over five decades collected for this study.

To measure the effects of water right security on land use, we use high-resolution satellite imagery from the U.S. Conterminous Wall-to-Wall Anthropogenic Land Use Trends (NWALT) geospatial dataset available from 1974 onward (Falcone, 2015), matched to reservation parcels by Dippel et al. (2020). These data allow for land use to be observed over a span of 40 years. NWALT data provide estimates of 19 categories of land use at a 60×60m resolution for five time periods — 1974, 1982, 1992, 2002, and 2012 — and have been cross-checked and validated using county-level USDA and U.S. census data, and numerous other federal land use and geospatial databases. We categorize land use as agricultural if it falls into one of two NWALT categories: crops or hay/pasture (Spangler et al., 2020). We also measure developed land use, though that is not our core focus.[5]

Our unit of analysis is a Public Land Survey System (PLSS) quarter section. The PLSS is a rectangular grid that served as the original basis for land surveying and settlement across much of the United States. The PLSS divides most of the U.S. into 6×6-mile townships. Townships are then divided into 36 1-mile×1-mile sections. Each section is divided into four quarter sections that are $\frac{1}{2}$-mile×$\frac{1}{2}$-mile squares (see Figure A2). These 160-acre quarter sections correspond to the typical size of an ownership tract on a reservation due to historical land titling policies, and conform to reservation boundaries (Leonard et al., 2020; Dippel et al., 2020).[6] For brevity, we refer

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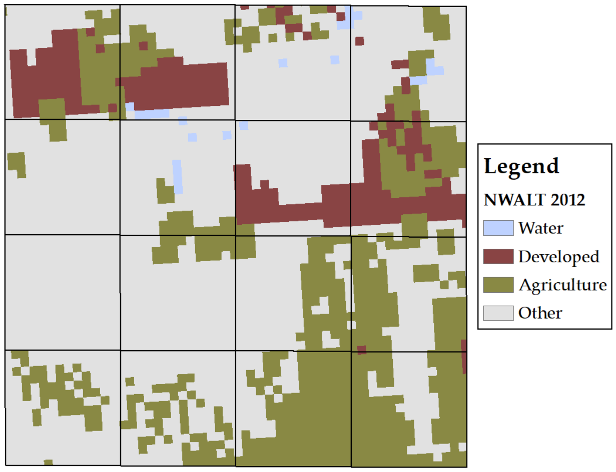
[5] NWALT includes a variety of developed land uses including major transportation, commercial services, industrial and military, recreation, high density residential, low-medium density residential, and "other developed land."' We categorize land use as "developed" if it falls into any of these development classes (Medalie et al., 2020).

[6] Some sections are divided into varying numbers of "government lots" rather than quarter sections, and this was

Figure 1: NWALT Land Use Data



Notes: This figure depicts our outcome measure of agricultural and developed land in the NWALT data. The figure depicts 16 quarter-sections of 160 acres each. The quarter-section is our unit of analysis. Light blue color shading indicates water, which we omit from the denominator when calculating the percentage of each parcel that is devoted to agriculture or development.

to quarter sections as "parcels," but we note that some quarter sections may contain multiple land parcels. Our primary outcome of interest — agricultural land use — is calculated as a percentage of total usable parcel area, which excludes water and wetlands. Figure 1 shows the NWALT data across a sample of 16 adjacent quarter sections.

Our sample includes a panel of 257,187 parcels on 57 federally recognized reservations in the U.S. west that have asserted water right claims for agricultural and domestic water use (Figure A3). We define our treatment group (n=144,933) as parcels located on 24 reservations that adjudicated their water rights via negotiated settlement between 1974 and 2012 (years of land use data availability). Our untreated group is comprised of 112,254 parcels located on 33 reservations that have initiated but not completed the adjudication process. We restrict our untreated group to parcels on reservations that have self-selected into the adjudication process but have not yet secured legal titles to water. We also exclude reservations that primarily pursue instream flow claims, as major changes to land use are less likely to occur after settlements on these reservations.

We use primary data collected by Sanchez et al. (2020) on the status of tribal water right adjudications from settlement agreement texts housed at the University of New Mexico's Native American Water Rights Settlement Project, and from state, appellate, and district court documents detailing ongoing, but unresolved, water right adjudications. We define a water settlement dummy

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especially true of Indian Land Patents issued under the Dawes Act. These government lots are typically 40 acres rather than 160. The upshot is that actual parcel sizes vary within the data to some degree, though the majority are 160 acres.

variable, $PostSettlement_{rt}$, where each parcel on reservation r is assigned a value of 1 for each year, t, following the enactment of the reservation's water settlement and zero prior to settlement.[7]

To assess potential differences between the treated and untreated groups, we create several measures of land quality.[8] We also include information on land tenure for each parcel from Dippel et al. (2020), which we describe in Section 5.[9] We construct two reservation-level, time-varying dummy variables for the presence of a casino or a tribal lending institution. For each indicator, parcel i on reservation r is assigned a value of one in year t if a casino/lending institution was in operation in that year, and zero otherwise.[10] We use U.S. Census data to estimate the off-reservation population in counties overlying or adjacent to reservations in each year.[11]

Finally, we collect administrative information on tribal water use from several sources. We consult settlement agreement texts, state water right databases, and reports from the Federal Bureau of Reclamation (USBR) to identify leases of tribal water to off-reservation users and environmental uses of tribal water rights such as instream flow for fish habitat or aquifer recharge. We also use estimates of water use developed by the USBR for a subset of reservations (U.S. Bureau of Reclamation, 2018).

3.2 Empirical Strategy

3.2.1 Difference-in-Differences

We use a difference-in-difference methodology to estimate parcel-level changes to land use before and after a water right settlement on treated versus untreated parcels, taking advantage of the fact that different reservations settled their water rights at different times, and that some reservations

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[7] In almost all cases, a tribe's water rights, as specified in a settlement agreement signed between negotiating parties, are formally defined when a water settlement is enacted by Congress. However, a handful of water settlements, such as the San Luis Rey settlement in Southern California, were enacted by Congress prior to negotiating parties reaching an agreement about how a tribe's water right would be satisfied. In these instances, we consider the later settlement agreement rather than the settlement act as the functional date of settlement completion.

[8] We use 30-meter×30-meter resolution data from the National Elevation Dataset to estimate each parcel's mean elevation and standard deviation of elevation as a measure of ruggedness (Ascione et al., 2008). We use the Schaetzl et al. (2012) soil productivity index (PI) as a time-invariant, estimate of mean soil quality on each parcel. The soil productivity index is ranked categorically from 0-21 with values greater than 10 representing highly productive soils.

[9] Figure A4 depicts an example of the parcel-level land tenure data for the Fort Peck Reservation in Montana.

[10] We collected data on casino operation from the National Indian Gaming Commission and individual casino websites. Data identifying tribal lending institutions are available from the Federal Reserve Bank of Minneapolis. We collected supplemental data on tribes served by each institution, including dates of operation, from the institutions' individual websites.

[11] We use the closest available census year to each of the five NWALT waves (1974, 1982, 1992, 2002, and 2012).

have begun the negotiation process but have yet to settle their rights. The typical approach for recovering difference-in-difference estimates of the average treatment effect on the treated (ATT) in our setting would be to use a two-way fixed effects estimator (TWFE) of the form:

$$y_{irt} = \beta_{TWFE} PostSettlement_{rt} + \beta_2 X_{rt} + \lambda_i + \tau_t + \varepsilon_{irt} \tag{1}$$

where Y_{irt} is the outcome for parcel i on reservation r in year t. X_{rt} is a set of time-varying reservation characteristics (adjacent-county population, an indicator for casino development, and an indicator for access to tribal lending institutions), λ_i is a vector of parcel fixed effects, and τ_t is a vector of year fixed effects.

The coefficient on $PostSettlement_{rt}$ has traditionally been interpreted as the difference-in-difference coefficient, but recent work has revealed potential problems with this interpretation. The core issue is that β_{TWFE} can deliver biased estimates of the true ATT when different cohorts (in our case, reservations) are treated at different times if there is substantial heterogeneity in the treatment effects over time or between cohorts (de Chaisemartin and d'Haultfoeuille, 2020; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Wooldridge, 2021). This bias arises because β_{TWFE} is a weighted average of all 2×2 comparisons of "switchers" to "non-switchers" that appear in the data, which includes: i) comparisons of switchers to never-treated parcels, ii) comparisons of early switchers to non-yet-treated parcels, and iii) comparisons of late switchers to already-treated parcels (Goodman-Bacon, 2021). The third comparison, where already-treated parcels act as a control group for late-treated parcels, can lead to negative weights in the weighted average represented by β_{TWFE}, resulting in a downward bias or even a negative coefficient when all underlying ATTs are in fact positive (de Chaisemartin and d'Haultfoeuille, 2020).[12]

de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2021) both describe the problems that can cause β_{TWFE} to deliver a biased estimate of the ATT and propose alternative DiD estimators that are robust to heterogeneous treatment effects across time and/or cohorts. To briefly summarize, both estimators are similar in that they use only never-treated or not-yet-treated units as control groups, eliminating the already-treated versus late-treated comparison.

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[12] These problems are more likely to arise as treatment effects become more heterogenous either across time or between treatment cohorts. See de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2021) for additional details.

de Chaisemartin and d'Haultfoeuille (2020)'s method provides time-specific ATTs for each k period since treatment that are averaged across different cohorts that are treated at different times, whereas Callaway and Sant'Anna (2021) construct group-time-specific ATTs (a separate ATT for each cohort in each of the k periods since treatment). Both estimators also include methods for aggregating ATTs across time/groups to deliver either event-study coefficients or an overall ATT that is averaged across all post-treatment periods.

We use de Chaisemartin and d'Haultfoeuille (2020)'s estimator as our preferred approach, but we show that the results are similar using either the Callaway and Sant'Anna (2021) estimator or the traditional TWFE approach.[13] We prefer the de Chaisemartin and d'Haultfoeuille estimator for two reasons. First, in practice, the Callaway and Sant'Anna estimator treats all covariates as time-constant, using only base-period covariates in the estimation, whereas de Chaisemartin and d'Haultfoeuille allow for time-varying covariate controls. A second, related advantage of the de Chaisemartin and d'Haultfoeuille estimator is that it allows the researcher to include nonparametric time trends for different groups. We discuss below why this is an important consideration in our setting.

3.2.2 Identification

Identification of the ATT associated with settling Winters rights using the de Chaisemartin and d'Haultfoeuille (2020) estimator requires several assumptions. In addition to some regularity conditions, we must assume that both the untreated and treated potential outcomes for the treated and untreated groups follow parallel trends, and that any shocks affecting the potential outcomes for either group are uncorrelated with treatment.[14] Examination of event study estimates from the de Chaisemartin and d'Haultfoeuille approach can provide some suggestive evidence in support of these assumptions, but ultimately, they are not testable.

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[13] Sun and Abraham (2021) and Borusyak et al. (2021) also propose related estimators, but their focus is on dynamic TWFE designs (event studies). We do not use those estimators for several reasons. First, we do not pursue an event study as our primary design due to the nature of our data and outcomes of interest. Our data occur at low frequency (once per decade) and we only observe five periods, limiting the insight that can be gleaned from an event study design. Moreover, some of the dynamic lead and lag coefficients would be identified off of a single reservation. Second, the Sun and Abraham estimator is similar in practice to the Callaway and Sant'Anna (2021) estimator, except that it excludes non-yet-treated units from the control group. Finally, the Borusyak et al. estimator requires relatively stringent assumptions for identification and may be more subject to bias than our preferred estimators if the parallel trends assumption does not strictly hold (de Chaisemartin and D'Haultfœuille, 2021).

[14] The regularity conditions include: i) there is a balanced panel of *groups*, ii) treatment is sharp (binary), iii) groups are independent, and iv) there exists a group of non-switchers for each set of switchers in the data.

Our first step in trying to justify the assumptions necessary for identification is to select an untreated group of reservations that is likely to be similar to the treatment group. Hence, our sample only includes reservations that have at least started the adjudication process. In addition to the 24 reservations that settled Winters rights between 1974 and 2012, another 33 initiated a claim but had not settled by 2012. We include these latter reservations as our untreated group.[15] Although Table A1 indicates some baseline differences between these groups in 1974, identification relies on the comparison of *trends* and *shocks* across these two groups that may be correlated with the timing of treatment, rather than level differences.

Figure 2 depicts the start and end dates of each reservation's adjudication, along with dashed lines for the years in which we observe land use. Reservations are stacked by when their adjudications *starts*, and color-coded based on when they enter the treated group in our data (the *ending of their adjudication*). As the figure indicates, the length of adjudications is highly variable. Many reservations that begin adjudicating at the same time nevertheless settle at different times, whereas some reservations that begin the process at different times settle simultaneously (through a single act of Congress).

As discussed in Section 2, Sanchez et al. (2020) find that the speed with which settlement occurs after a tribe initiates the adjudication process is driven by the majority party in Congress and the number of off-reservation parties included in the adjudication, which are both exogenous to the reservation. This interpretation is also consistent with our conversations with various policy stakeholders who have been involved in the adjudication process.

Despite the largely exogenous nature of congressional actions to finalize Winters settlements, reservation or state-specific shocks could violate the identifying assumptions if they are correlated with the timing of treatment (settlement) and with changes to reservation land use.[16] We take several additional steps to address these concerns and diagnose their likely importance for our results.

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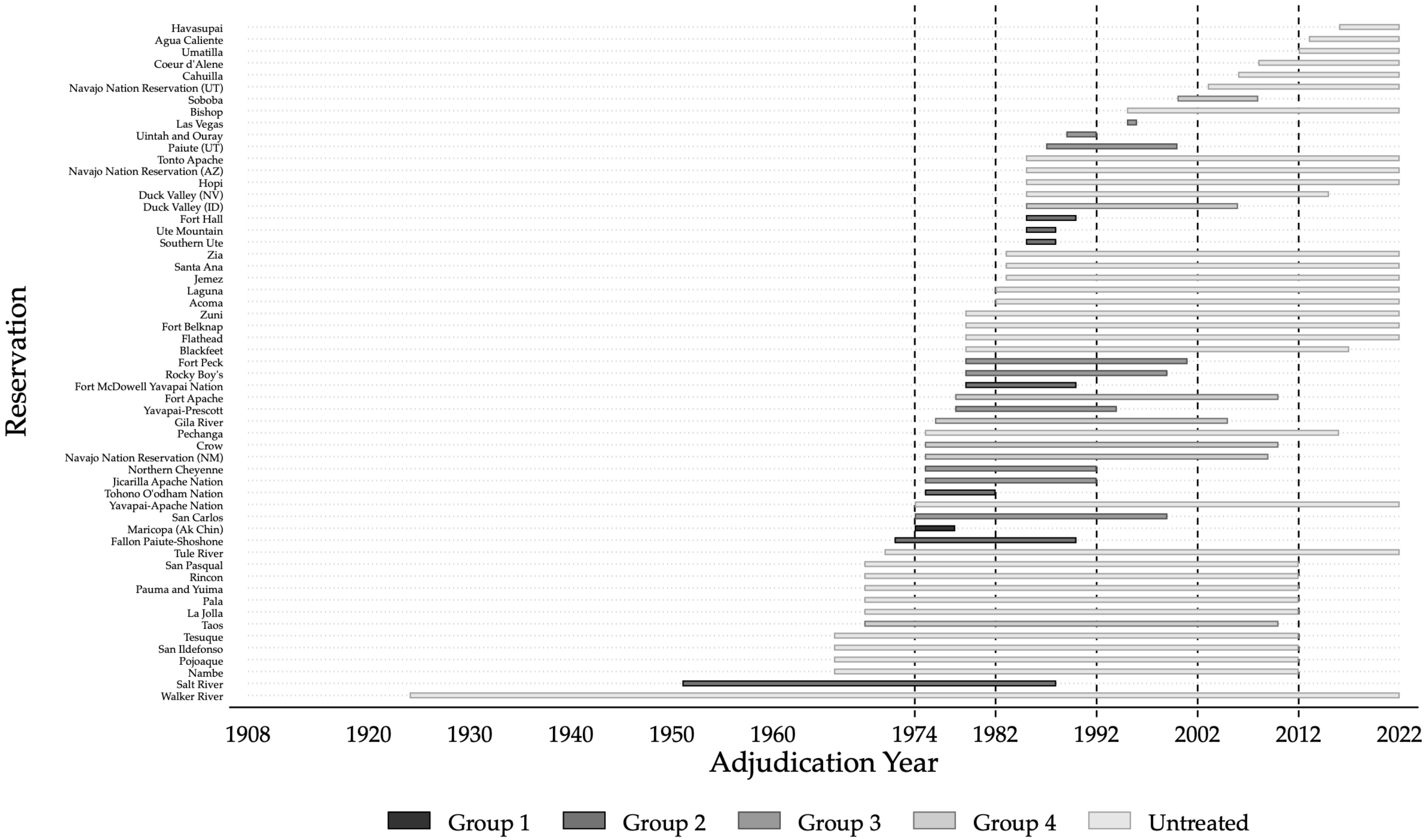
[15] While conditioning on starting the adjudication process is useful for identification, it may limit the external validity of our results for understanding the potential impact of Winters settlements on tribes that have not yet begun the adjudication process.

[16] To provide additional evidence that the timing of adjudication is not driven by on-reservation factors, Appendix Figure A5 depicts reservation-level scatter plots of 1974 land use, 1974 off-reservation population, date of first casino opening, date of first banking access, distance to the nearest perennial stream, average precipitation, and average temperature against adjudication start dates for treated and untreated reservations.

Figure 2: Timeline of Winters Adjudications & Settlements



Notes: This figure depicts adjudication start and end dates for each reservation in our sample. Reservations are grouped into timing cohorts based on the decade when the adjudication was completed. Untreated reservations that are still undergoing the adjudication process as of 2012 act as a control group. Vertical dashed lines indicate the years in which we observe land use from the NWALT data.

We include state-specific non-parametric time trends to capture shocks to water resources and water demand — as well as potential changes in state water policy that could affect the outcome of Winters negotiations — when we use the de Chaisemartin and d'Haultfoeuille estimator.[17] There were a variety of state-level changes to water policy during our study period that may have affected negotiations. Some examples include the state-by-state adoption of in-stream flow rights (Boyd, 2003), the construction of the Central Arizona Project (Glennon, 1995), and new groundwater regulations (Jacobs and Glennon, 1992). In the absence of flexible controls for year effects that vary by state, these events may compromise identification.

We also include several time-varying reservation-level controls that could influence the evolution of land use on reservations. These common controls from the literature on Native American development help capture time-varying differences in reservations' economic development and institutional capacity that may otherwise violate the parallel trends assumption. First, we include off-reservation population in adjacent counties. While this is unlikely to directly affect reservation land use, it may be correlated with treatment because increasing water scarcity is associated with a higher likelihood of adjudication (Sanchez et al., 2020). Second, we include a dummy variable that is equal to one if a reservation has an active casino. The presence of casinos on reservations is a potentially important control because the presence of successful casinos may be indicative of tribal institutions that are amenable to making the types of large, coordinated investments necessary for putting Winters rights to use (Deol and Colby, 2018).[18] Finally, we include a dummy variable that is equal to one if a reservation has a tribal lending institution in a given decade, which has been shown to lead to greater agricultural land use over the period we study (Dippel et al., 2020).[19] Throughout the paper we report results with and without the inclusion of these controls.

As a final point regarding identification, we emphasize that we do not anticipate spillover effects of water right adjudications across reservations. Reservations are generally spatially dispersed enough to prevent a downstream reservation from benefiting from return flows from an upstream reservation's water use. Likewise, land use change in anticipation of settlement is unlikely, as a tribe's water rights must be clearly defined before the tribe can enforce water deliveries

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[17] We replace these with state-by-year fixed effects when using the the TWFE estimator.

[18] This variable is equal to zero for all reservations before 1992, but it varies by reservation thereafter. The passage of the Indian Gaming Regulatory Act in 1988 allowed tribes to begin operating casinos.

[19] Table A2 shows the evolution of these variables over time and reveals differences between reservations that never receive treatment versus those that settle between 1974 and 2012.

or lease that water to others. Moreover, many tribes lack the physical diversion infrastructure (or the capital to develop it rapidly) to begin diverting and using water in anticipation of a settlement (Government Accountability Office, 2006).

4 Main Results

This section presents the main results of our estimates of the impact of Winters rights settlement on reservation land use. We also provide back-of-the-envelope calculations for what our estimates imply in terms of actual *water* use under a variety of assumptions about water use per acre. In all results, we cluster standard errors by PLSS townships, which are arbitrary 6×6-mile squares, as is common in studies of agricultural land and water use (Ge et al., 2020; Hagerty, 2021).[20]

4.1 The Effect of Winters Rights on Agricultural Land Use

We begin by presenting event study estimates to provide evidence for whether the necessary parallel trends assumptions are likely to hold in our setting. The relevant comparison for identification purposes requires focusing on trends in the untreated group relative to a treated reservation *at the time of treatment*, i.e., an event study. de Chaisemartin and d'Haultfoeuille (2020)'s estimator allows the researcher to estimate the effect of treatment in each of the k periods before versus after treatment. Our NWALT data contain a total of five periods. Because settlements are staggered over time, we are able to report a symmetric window that includes three periods prior to treatment and three years after treatment, with period "0" defined as the first year in which treatment begins. Sizing the event window in this way ensures that dynamic leads or lags are not being identified by a single reservation.[21]

Figure 3 presents the results of the event study estimates using the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) for our baseline specification that includes parcel fixed effects and state-specific non-parametric trends, but no time-varying reservation controls. All coefficients are relative to the difference between treated and untreated parcels in the period just prior to treatment, which is normalized to zero. The coefficients for periods $t-2$ and $t-3$ are

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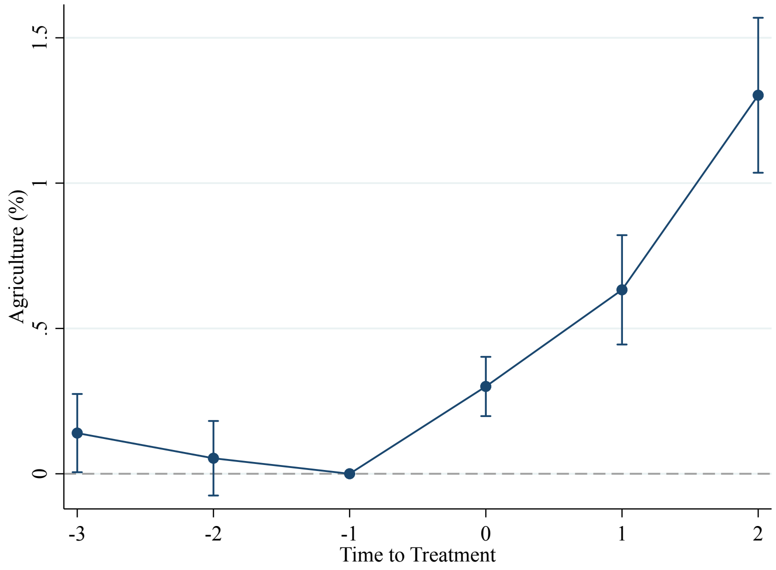
[20] A typical township has 144 quarter-sections. Clustering at a higher level, like reservations, is not feasible because of the small number of reservations in our sample, given that we cannot combine the new DiD estimators with techniques for valid inference with low numbers of clusters, such as the wild cluster bootstrap (MacKinnon and Webb, 2017).

[21] We have only one reservation, Maricopa (Ak-Chin), for which we observe three time periods of data after period "0." Accordingly, we focus our event window on period 0 plus two years.

near zero and statistically insignificant. The period $t-3$ coefficient is near to significance, but this suggests a *decreasing* trend in agricultural land use on treated reservations prior to receiving a water right. From period $t=0$ onward, there is a statistically significant (and increasing) difference between treated and untreated parcels.[22]

Our main estimates for the effect of Winters rights on agricultural land use are presented in Table 1. The baseline model in column 1 does not include any time-varying reservation controls. Column 2 controls for off-reservation population growth, column 3 controls for casino presence, column 4 controls for credit access, and column 5 includes all three controls. Panel A reports estimates from de Chaisemartin and d'Haultfoeuille (2020)'s method, Panel B reports estimates using the Callaway and Sant'Anna (2021) estimator, and Panel C reports estimates obtained using the classic TWFE approach.[23] Panel A includes state-specific non-parametric trends and Panel C includes state-by-year fixed effects, but Panel B includes only year fixed effects.[24]

Figure 3: Agricultural Land Use Event Study



Notes: This figure depicts event study estimates using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The model corresponds to the specification in column 1 of Panel A of Table 1, which includes parcel fixed effects and state-by-year fixed effects. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment.

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[22] Appendix Figure A6 shows that this finding is robust to including time-varying controls for off-reservation population, casino presence, and credit access. Appendix Figure A7 presents event study results using the Sun and Abraham (2021) estimator (using the `eventstudyinteract` command) that are similar to our preferred estimates. Together, these figures provide support for the common trends and exogeneity assumptions necessary for identification.

[23] Panel A estimates are derived using with the `did_multiplegt` package in Stata. Panel B estimates are derived using the `csdid` package in Stata.

[24] The Callaway and Sant'Anna (2021) estimator does not have an option for including group-varying time effects.

The coefficient estimates in Table 1 are fairly stable across specifications and different estimators. The dependent variable is the percentage of a quarter section devoted to agricultural land use (ranging from 0 to 100). Controlling for time-varying reservation covariates tends to increase the estimated effect of Winters settlements, especially when all three controls are included. Hence, although inclusion of time-varying controls does not appear critical for the parallel trends assumption, it may nonetheless lead to a more credible comparison between reservations in the treated versus untreated groups that were on similar land use trajectories.[25] The coefficients are also fairly consistent across all three estimators. The TWFE and Callaway and Sant'Anna (2021) estimates are quite similar, whereas the de Chaisemartin and d'Haultfoeuille (2020) tend to be somewhat larger.

Table 1: The Impact of Winters Settlements on Agricultural Land Use

	(1)	(2)	(3)	(4)	(5)
	Y = % Agriculture				
Panel A:					
	de Chaisemartin & D'Haultfoeuille (2020)				
Post Settlement	0.526	0.588	0.582	0.526	0.614
	(0.065)	(0.065)	(0.061)	(0.066)	(0.066)
Panel B:					
	Callaway & Sant'Anna (2020)				
Post Settlement	0.392	0.342	0.408	0.457	0.500
	(0.062)	(0.160)	(0.060)	(0.114)	(0.221)
Panel C:					
	Two-Way Fixed Effects				
Post Settlement	0.209	0.292	0.348	0.201	0.360
	(0.068)	(0.068)	(0.065)	(0.067)	(0.064)
Observations	1,410,185	1,410,182	1,410,185	1,410,185	1,410,182
Adjusted R-squared (TWFE)	0.979	0.979	0.979	0.979	0.979
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents difference-in-difference estimates for the effect of Winters settlements based on the model in Equation 1 using several estimators. Panel A uses the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and implemented with the `did_multiplegt` Stata package with two leads and two lags of treatment. Panel B uses the estimator proposed by Callaway and Sant'Anna (2021) and implemented with the `csdid` package in Stata. Panel C presents traditional TWFE estimates obtained via OLS. Panels A and C include state-by-year fixed effects, whereas Panel B uses pooled year fixed effects due to limitations of the `csdid` package. Standard errors are clustered by PLSS township (a 6×6-mile square containing 144 parcels) and reported in parentheses.

Although we find a robust and precisely estimated increase in agricultural land use after Winters settlements, the magnitude of the effect is small. Focusing on the largest of the coefficients in

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[25] We do note, however, that controls for casino presence and tribal lending institutions may be endogenous because those tribes with the institutional capacity to pursue casinos and lending institutions may fare better in Winters negotiations.

Panel A of Table 1, column 5 suggests a 0.614 percentage point increase in agricultural land use due to a Winters settlement. The average untreated parcel is 7.04 percent agriculture, implying that settlement leads to a 8.7 percent increase in agriculture relative to the mean. In the Appendix, we show that our core results are robust to a variety of alternative specifications, controls, and ways of measuring agricultural land use.[26] We also explore the impact of Winters settlements on developed land use. Because the estimates are a full order of magnitude smaller than the agricultural land use estimates and agricultural water use per-acre is much higher than residential and urban water use per-acre, our analysis focuses primarily on agricultural land use and these results are left to the Appendix.[27]

4.2 Water Use Estimates

We use our agricultural land use estimates to develop back-of-the-envelope estimates of i) predicted changes in water use due to settlement and ii) total water use on each reservation in 2012. This allows us to characterize the proportion of settlement water being used by each tribe, and how much of this use is attributable to post-settlement changes in land use associated with our main causal estimates.

We use the estimates from column 5 in Panel A of Table 1 to calculate the share of total reservation water use that is attributable to changes in land use associated with the settlement of a Winters right.[28] To do so, we take the average predicted change in land use for a parcel and multiply by the average parcel size and number of parcels on each reservation. We multiply this figure by varying levels of water use ranging from 2 to 5 acre-feet per acre (AFA).[29] We estimate the predicted change in reservation water use according to the following calculation:

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[26] Columns 1 and 2 of Table A3 focus on cultivated crops only, excluding hay/pasture. Columns 3 and 4 of Table A3 use a linear probability model where the dependent variable is equal to one if a parcel has any agricultural land use, and zero otherwise. Columns 1–4 of Table A4 add information about the depth-to-groundwater table, where available. Finally, columns 5 and 6 of Table A4 replace state-by-year fixed effects with start date-by-year fixed effects that group reservations into seven cohorts based on when they *began* the adjudication process and allows differential time effects for each cohort. Essentially, this approach matches each treated reservation to at least one untreated reservation that began the adjudication process at the same time but finished at different times, and allows them to share year-specific shocks.

[27] Columns 5 and 6 of Table A3 present the developed land use results. Unlike the agricultural land use results, the developed coefficient estimates are statistically insignificant across all models and estimates. Although these effects are clearly not precisely estimated zeroes, we fail to reject the null that Winters' settlements have no effect on developed land use.

[28] We use the column 5 coefficients to generate the largest (most optimistic) predicted increase in water use.

[29] This covers the range of water use per acre for the most common crops grown in the U.S. West (Johnson and Cody, 2015), which varies from 0.6 AFA for berries to 5 AFA for sugar beets.

$$\Delta \hat{U}se_r = \frac{\hat{\beta}_{ag}}{100} \times AFA_{ag} \times \overline{ParcelAcres_r} \times N_r^P \tag{2}$$

where N_r^P is the number of parcels on reservation r, and $\overline{ParcelAcres_r}$ is the average size of parcels on reservation r. $\hat{\beta}_{ag}$ is the de Chaisemartin and d'Haultfoeuille (2020) coefficient estimating changes to agriculture land use from column 5 of Panel A in Table 1.

We estimate that the average settlement-induced changes in on-reservation water use across reservations account for 5–12% of tribes' total water entitlements, depending on assumptions about water use per acre. When we include off-reservation leasing, our estimates of post-settlement changes to water use increase to an average of 8–16%. The extent to which tribes lease water rights off-reservation is highly variable, with a few reservations in the Southwest leasing large portions of their water entitlements.

The results for each reservation are depicted in Figure 4, which shows calculated changes to reservation water use corresponding to an agricultural water use of 2, 3, 4, or 5 AFA. The outcome — expressed as a percentage of total entitlements — is affected by three factors: assumptions about water use per-acre, the estimated change in agricultural acreage post settlement, and the total water entitlement secured in the settlement. The range of water use scenarios is higher for reservations whose change in agricultural land use is larger relative to total entitlement. For example, on the Tohono O'odham Nation (TON) estimates vary from just over 40% with 2 AFA, to 100% of its entitlement with 5 AFA.

Next, we estimate *total* water use in 2012 for each treated reservation to better understand plausible water use scenarios. We separately sum agricultural acres and developed acres from the 2012 NWALT data by reservation and multiply by conversion factors for water use per acre. We assume that developed land uses an average of 0.25 acre-feet (AF) per acre.[30] We estimate the share of settlement water use on reservation r in 2012 as:

$$\hat{U}se_r = AgAcres_r \times AFA_{ag} + DevAcres_r \times 0.25 + Leased_r \tag{3}$$

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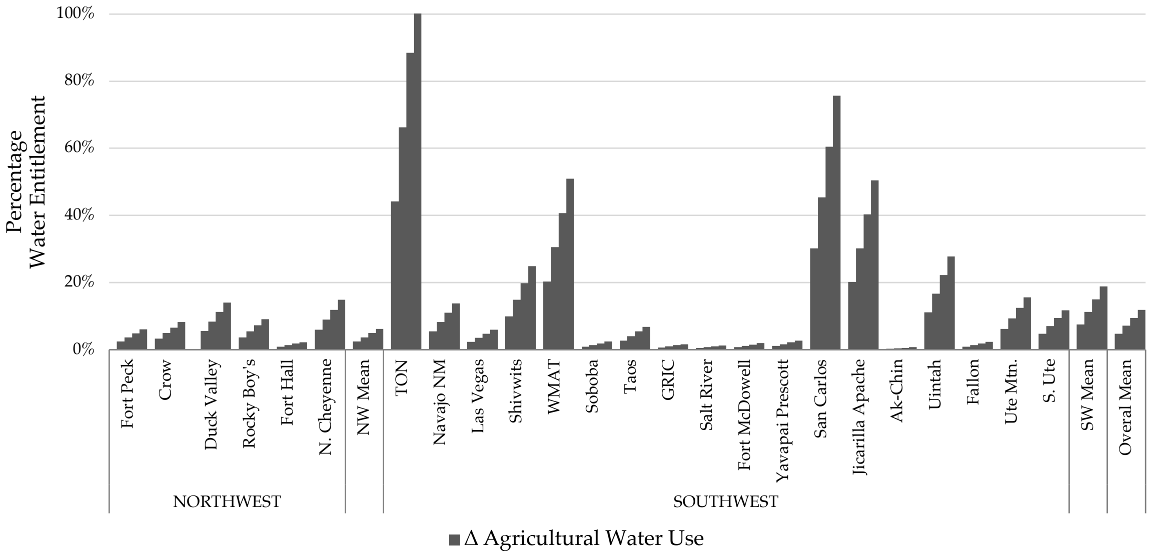
[30] To arrive at our 0.25 AF per acre water use estimate for urban water use on reservation we use the average 4-person household water use for Arizona and California provided by (Pitzer, 2018) of 0.33 AF/year and scale it by the average on-reservation, in-town population density in Arizona of about three people per acre (Center, 2015). We view this as an upper-bound assumption as 48 percent of reservation households lack access to water and sanitation infrastructure (Democratic Staff of the House Committee on Natural Resources, 2016).

Figure 4: Estimated Change in Water Use Relative to Entitlements



Notes: This figure depicts the estimated change in water use for each treated reservation in our sample using Equation 2 and the coefficient from column 5 of Panel A in Table 1. For each reservation, water use estimates depicted by each bar, from left to right, assume agricultural water use estimates of 2, 3, 4, and 5 AF/acre.

where $Leased_r$ is water being leased to off-reservation users by reservation r in 2012, which we obtain from settlement agreements and water transaction records for each state. We censor our estimate at 100 percent in cases where predicted water use exceeds available water.

Figure 5 depicts estimates of the share of used, leased, and unused settlement water for each treated reservation in the sample. Our estimates again show considerable heterogeneity across reservations. For instance, Fort Peck is using its entire entitlement under all four scenarios, as are several other reservations under high water-use scenarios. Others, like Soboba or Taos, were using little to none of their settlement by 2012.

The results also reveal that some reservations such as Crow and Fort Peck have a small predicted effect of settlement in Figure 4, but nevertheless have high overall water use in 2012.[31] This suggests that some tribes may pursue Winters settlements to solidify rights to water they are already using. Additional analysis contained in the Appendix, however, suggests this is unlikely to be a key explanation for the small magnitude of our estimated treatment effect.[32]

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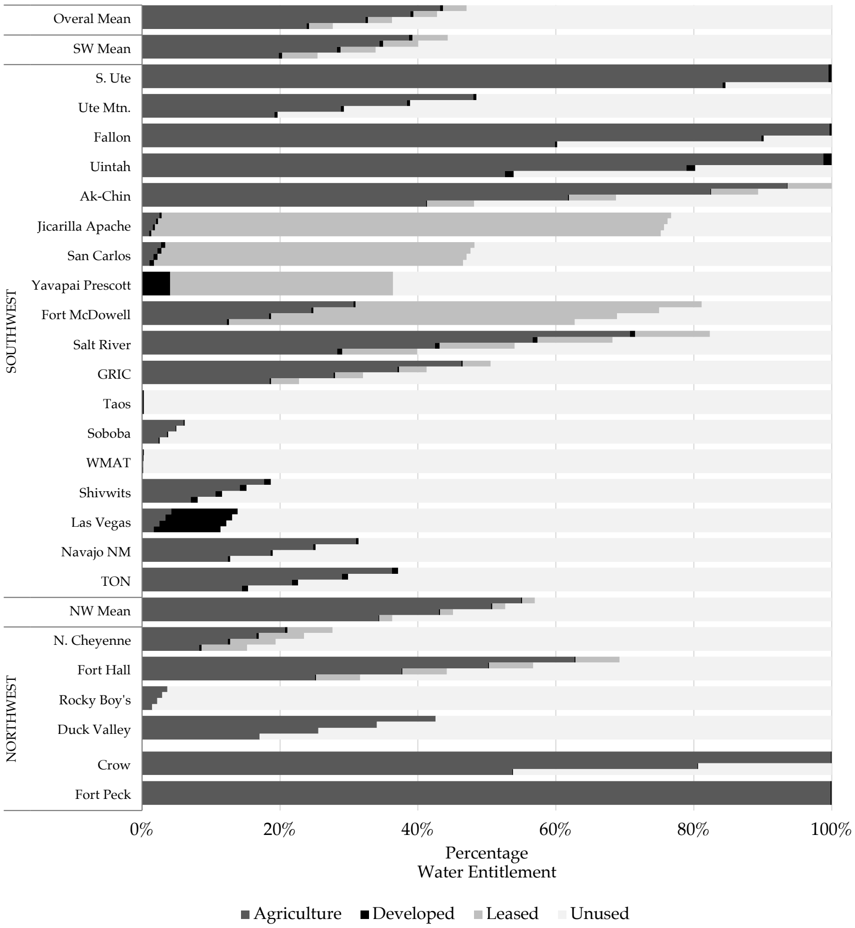
[31] Conversely, for some reservations like the Tohono O'odham Nation, we estimate low overall utilization of Winters rights in Figure 5 despite predicting that these reservations would use a large share of their settlement water in Figure 4. The reason is that these reservations have a large land base and a relatively small amount of settlement water. Hence, applying the average percentage increase in agricultural land use from Table 1 yields large predicted changes in land (and therefore water) use.

[32] To test whether tribes using settlement to solidify rights to water they are already using is suppressing the overall treatment effect we estimate in Table 1, we estimate the share of each reservation that is already in agricultural land

Figure 5: Total 2012 Water Use Estimates



Notes: This figure depicts estimated water use in 2012 for each treated reservation in our sample using Equation 3. The estimates include water for agriculture, developed land use, and off-reservation water leasing. We assume 0.25 AF/acre for developed land use. For each reservation, water use estimates depicted by each bar, from bottom to top, assume agricultural water use estimates of 2, 3, 4, and 5 AF/acre. The lightest gray shaded area represents the share of a reservation's water settlement that we estimate is unused in 2012.

4.3 Validation and Implications of Water Use Estimates

While data documenting actual tribal water use are notoriously scarce, we validate our 2012 water use estimates by comparing them to data compiled by the Bureau of Reclamation in a 2018 report on tribal water use (U.S. Bureau of Reclamation, 2018). The report estimates current and future water use of ten federally recognized tribes in the Colorado River Basin.[33] It uses data provided by

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use at the beginning of the sample 1974. Figure A8 depicts a histogram of 1974 agricultural land use, and indicates that most reservations were using less than 20% of their land for agriculture in 1974. We test for heterogeneity along this margin by interacting the post-treatment indicator with an indicator for whether a reservation had greater than 5, 10, or 20% agricultural land use in 1974. The results in Table A5 indicate that the effect of settlement is not statistically different based on the share of a reservation in agriculture in 1974.

[33] The Ten Tribes Partnership, formed in 1992 by ten federally recognized tribes with federal Indian reserved water rights in the Colorado River or its tributaries, includes five tribes from our sample with settlement water rights and five tribes not in our sample that adjudicated via court decree in 1963.

individual tribes to measure water use for agriculture, development, leasing, and environmental purposes. Although data availability and quality differ across reservations, the report offers one of the few snapshots of current tribal water use. Figure A9 includes our estimates of current water use alongside USBR's for comparison.[34] Water use estimates provided by USBR generally fall within the range of estimated water use predicted by our models.[35]

Another important consideration is that land use change due to Winters rights may take time to manifest. The inclusion of the largest $t = 2$ coefficient from panel (d) of Figure A6 (1.63), instead of the overall post-treatment mean (0.614) shows that water use estimates still represent a small share of entitlements for most reservations.[36] Hence, our core finding that most tribal water rights have not yet been utilized is not sensitive to our focus on an overall average post-treatment effect.

By summing up the gray portions of the entitlements depicted in Figure 5, we can estimate how much additional water tribes could use in the future, even if no additional Winters settlements occur. Full utilization of existing Winters rights would amount to an *additional* 1.1 to 2.6 million acre-feet of tribal water use annually relative to our 2012 estimates, indicating the potential for major changes in Western water use, even without additional legal developments. To get a sense of the economic significance of this volume of water, we use data on 7,000 water transactions between 2002-2019, as summarized in Burns et al. (2022), to estimate state-specific average per acre-foot prices for water. We then multiply our estimates of unused entitlement water for each reservation by the average price in the associated state. Summing across all reservations, we find that the value of yet-to-be-utilized tribal water entitlements could range from $938 million to $1.8 billion in leasing revenue annually.

5 Understanding the Underutilization of Winters Rights

In this section, we consider several potential explanations for the apparent underutilization of Winters rights implied by our results in Section 4. We recognize that there are a litany of factors

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[34] These include a combination of 2008-2013 averages, and 2012 estimates depending on data availability

[35] In cases where our estimates differ, they *overstate* estimated tribal water use relative to USBR. While data constraints prevent us from validating our estimates for a broader sample of reservations, the available evidence suggests that the broad finding that many tribes are not using a large portion of their entitlement is not driven by our modelling assumptions. Further, the USBR estimates that environmental water use accounts for only .02 percent of settlement water entitlements, suggesting that this category does not explain the large gap between use and entitlement amount in our estimates.

[36] In Appendix Figure A10 we reproduce Figure 4 to allow for this possibility.

that could contribute to limited use of Winters rights, and that many of these factors may be unique to each reservation in our sample. Rather than attempting to develop an exhaustive or definitive explanation for the magnitude of each tribe's unused Winters rights, we instead explore a broad set of potential contributing factors that may be common across a number of reservations, with the aim of informing future research and policy priorities.

Potential explanations for the volume of unused Winters rights — the gray areas in Figure 5 — can be parsed into two broad categories: barriers that constrain tribes' ability to utilize their new water rights and other goals/uses of Winters rights beyond those captured in Figure 5. We draw from three sources to identify potential barriers or competing goals for Winters rights: i) conversations with a diverse group of tribal representatives, lawyers, and state officials experienced with the Winters process; ii) the literature on water markets, infrastructure, and water use in the Western United States; and iii) the literature on reservation economic development and resource use. Next, we describe and assess the evidence for the barriers and alternative goals that we identified.

5.1 Barriers to Tribal Water Use

A variety of structural barriers may inhibit tribes from using Winters rights after they complete the settlement and litigation process. Two barriers to water use and investment that extend beyond reservations are the over-allocation of "paper" water rights that exceed "wet" water rights, and a lack of irrigation infrastructure. These issues may be compounded by institutional factors that are unique to reservations including land tenure and legal uncertainty that can stymie investment.

5.1.1 Water Availability

In many basins across the Western United States, there is a fundamental misalignment between legal claims to water and the actual water available within the hydrologic system. For example, the Colorado River Compact allocated 16.5 million acre-feet of water between the seven basin states and Mexico, but the annual flow of the river since 2000 has averaged only 12.3 million acre-feet (Wheeler et al., 2022). When water is structurally over-allocated, water rights that exist on paper may not be physically available for diversion and use.

Water availability (or the lack thereof) is an unlikely explanation for unused Winters rights for two reasons. First, settling or adjudication Winters claims typically triggers what is known as a "general stream adjudication" that evaluates all major claims within a basin to align legal water rights with hydrologic realities, allocating some rights to the tribe in the process. Because this process is designed to address systemic over-allocation, there should be a general match between water rights and average water availability once a settlement is complete. Second, even if water is still over-allocated to some degree, Winters rights are typically the most senior rights in a basin, as discussed in Section 2 and depicted in Figure A1. Put simply, if there is *any* water available to use in a basin, a tribe will have secure legal access to that water.

5.1.2 Water Infrastructure

Tribes may fail to use water if they are physically unable to divert that water from streams and put it to beneficial use. Many reservations are located in the West, where rivers and streams are separated by large expanses of dry, but otherwise arable, land. In this context, surface water irrigation relies on large-scale infrastructure to store, divert, and convey water from where it is typically found — in drainages too rugged for farming — to flat, arable lands (Hanemann, 2014; Leonard and Libecap, 2019; Edwards and Smith, 2018). Developing this infrastructure is costly. Off of reservations, private financing of ditches and other small-scale infrastructure in the late 19th century gave way to larger projects funded by the Bureau of Reclamation in the early 20th century (Hanemann, 2014). Without similar infrastructure, reservations face physical and logistical hurdles to using their water (Water & Tribes Initiative, 2021).

To assess whether the availability of infrastructure explains the small effect of Winters settlements on tribal water use, we exploit the fact the the Bureau of Indian Affairs constructed irrigation infrastructure projects on some reservations in the early 20th century.[37] Within our sample, seven treated reservations and two untreated reservations have BIA projects.[38] We estimate a difference-in-difference-in-difference model (DDD) where we interact our treatment indicator with a indicator for whether a reservation have a pre-existing BIA irrigation project and present the results in Table A6.[39] The results indicate that the effects of Winters settlements differ substan-

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[37] Although many BIA projects are sorely in need of repair today (Carlson, 2018), the presence of an existing project nevertheless provides a major logistical advantage for the tribes that have them.

[38] The treated reservations with projects are: Crow, Duck Valley (ID), Fort Hall, Fort Peck, Gila River, Southern Ute (CO), and Uintah & Ouray. The untreated reservations with projects are Fort Belknap and Southern Ute (NM).

[39] Unfortunately, the estimators proposed by de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2021) cannot be used to estimate a difference-in-difference-in-difference model. Given the similarity of the estimators in Table 1, we believe these TWFE estimates are reliable, especially for agricultural land use. Moreover,

tially based on the presence of a BIA infrastructure project. While generally the effect on reservations with no project is not statistically different from zero, the effect for reservations *with* BIA projects is significant across all five specifications and is roughly twice the magnitude of the baseline effect in Table 1. These results suggest that existing irrigation infrastructure is an important factor in tribes' ability to make settlement water available for immediate use.

5.1.3 Land Tenure

Due to a partially implemented scheme to privatize tribal land (implemented from 1887 to 1934 during the "Dawes Era"), many reservations are a patchwork of three categories of land: tribal trust land held by the federal government; fully private "fee simple" parcels, and "allotted" parcels that were allotted to individuals but never released from federal trusteeship (Carlson, 1981; Leonard et al., 2020).[40] Previous research has shown that trusteeship on allotted and tribal land prevents land use change and resource development via a complex nexus of transaction costs, credit constraints, and bureaucratic hurdles (Leonard et al., 2020; Leonard and Parker, 2021; Ge et al., 2020; Dippel et al., 2020).[41]

We use land tenure data developed by Dippel et al. (2020) to explore potential differences in the impact of Winters settlements across different land tenure regimes within treated reservations.[42] Parcels are categorized into three discrete land tenure groups: fee simple, tribal trust, and allotted trust land.[43] We estimate a difference-in-difference-in-difference (DDD) model that allows the

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by allowing for different treatment effects across different groups of reservations, we are flexibly incorporating heterogeneity into the model, reducing the likelihood that remaining heterogeneity will bias the TWFE estimates (Wooldridge, 2021). We present robustness checks using robust DiD estimators estimated separately for reservations with vs. without BIA projects in Panels A and B of Table A6.

[40] Beginning in 1887, the Dawes General Allotment Act authorized the Office of Indian Affairs to allocate tribal land to individual Native American households. These allotments were typically held in trust by the federal government for 25 years until the allottee was deemed "competent" to hold fee simple title. Allotted trust lands could not be transferred or included in an individual's will. The allotment process abruptly ended in 1934, essentially locking land tenure in place at that time. See Leonard et al. (2020); Dippel et al. (2020).

[41] The non-transferability of allotted trust lands precludes their use as collateral for accessing credit and has led to fractionated ownership due to common heirship, wherein a single trust parcel can be shared by over 100 owners who must agree to any changes in land use (Dippel et al., 2020). Tribal land avoids many of these pitfalls, but tribes must confront federal regulatory hurdles not present on private land due to federal trusteeship (Leonard and Parker, 2021).

[42] To focus on fixed differences in land tenure, we limit our sample to parcels that have not changed land tenure status since 1974 (the first year of land use data availability). In practice, this is the vast majority of parcels. We exclude parcels that have changed tenure status due to special circumstances so that our results are not confounded by factors that cause changes in tenure status, such as special acts of Congress.

[43] To deliver precise estimates of the effect of tenure, we exclude parcels that have a mix of land tenure associated with them. This would include allotted parcels where only a subset of the acreage was converted to fee ownership as well as parcels that were only partially allotted to begin with. The last three rows of Table A1 show the share of each type of ownership on treated versus untreated reservations. Overall, treated reservations have a larger share of fee

effect of Winters settlements to vary by land tenure class and report the results in Table A7. We find substantial differences in the impact of Winters settlements across land tenure classes. On fee simple land, settlement increases agricultural land use by roughly 0.95 percentage points, a 50 percent increase relative to the pooled coefficient in Table 1. In contrast, changes on allotted and tribal parcels are not statistically different from zero in most cases, suggesting that Winters settlements do not lead to any increases in agriculture on trust lands.[44]

To understand the relative importance of land tenure barriers, we construct a counterfactual of changes to land use as the result of a settlement under the alternative assumption that all parcels experienced the same increase in land use as observed on fee simple parcels:

$$\begin{aligned}\Delta \tilde{Use}_r = & \left(\frac{-\hat{\beta}^A_{ag}}{100} \times AFA_{ag}\right) \times \overline{ParcelAcres}^A_r \times N^A_r \\ & + \left(\frac{-\hat{\beta}^T_{ag}}{100} \times AFA_{ag}\right) \times \overline{ParcelAcres}^T_r \times N^T_r \end{aligned} \tag{4}$$

where $ParcelAcres^A_r$ and $ParcelAcres^T_r$ are the average size of allotted trust and tribal trust parcels, respectively, and N^A_r and N^T_r are the number of allotted trust or tribal trust parcels on reservation r. $\hat{\beta}^A_{ag}$ and $\hat{\beta}^T_{ag}$ are coefficients from column 5 of Table A7.

Next, we take the estimated counterfactual changes to water use and add them to our estimates of *actual* total water use from Equation 3 (and Figure 5) to construct a counterfactual estimate of what water use on each reservation would have been in 2012 in the absence of land tenure constraints: $\tilde{Use}_r = \hat{Use}_r + \Delta\tilde{Use}_r$. As a final step, we estimate the portion of unused water in the counterfactual 2012 scenario as $\hat{Unused}_r = Settlement_r - \tilde{Use}_r = Settlement_r - (\Delta\tilde{Use}_r + \hat{Use}_r)$. We express $\hat{Unused}_r$, $\tilde{Use}_r$ and $\Delta\tilde{Use}_r$ as shares of $Settlement_r$.

The results are depicted in Figure 6.[45] The darkest gray, solid shading indicates the estimated share of a settlement used in agriculture in 2012 and the black shading indicates the estimated share used in development in 2012. Lighter gray, solid shading indicates leased water. The darker striped shading corresponds to $\Delta\tilde{Use}_r$ and indicates how much more water would be used if the reservation were entirely fee simple land. The lighter striped shading corresponds to water that

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simple and allotted trust land, and a lower share of tribal trust land.

[44] Table A8 presents the tenure-specific results for developed land use. We find no effect of Winters settlements on developed land use across any of the land tenure classes or estimators.

[45] Appendix Figure A11 shows an alternative version using the $t = 2$ coefficient instead of the post-treatment average.

is unused even in the counterfactual scenario, and hence attributable to factors other than land tenure.

The results in Figure 6 indicate that constraints on land tenure are a meaningful barrier to expanding water use on some reservations but are less consequential on others. Differences across reservations appear to be driven by a combination of the amount of non-fee land on a reservation and the timing of a settlement. All else equal, reservations with large areas of tribal and allotted trust land stand to gain more in a counterfactual scenario where those parcels are free from trust land constraints.[46]

5.1.4 Barriers to Investment on Reservations

Finally, utilization of Winters rights might be constrained by a broader nexus of legal and institutional hurdles that have limited economic development and investment on reservations more broadly. For example, Crepelle (2019) identifies a variety of legal barriers to investment on reservations, Dippel et al. (2021) find that the adoption of uniform secured transactions laws can promote economic development, Cattaneo and Feir (2021) find that Native Americans face higher prices for mortgage financing, and Anderson and Parker (2008) find that questions about legal jurisdiction can hamper investment. Moreover, tribal infrastructure projects are subject to Endangered Species Act, National Environmental Protection Act, and state environmental regulations (Blumm et al., 2006). Hence, even though tribes have secure rights to water, barriers to investment on reservations more broadly may interact with the other mechanisms we study to further constrain tribes' ability to utilize their water rights.

In principle, settlement funding is meant to help address the problem of finance for infrastructure. However, tribes have struggled to secure annual payments because federal funding allocated through water settlements is often discretionary rather than mandatory (Stern, 2017; Water & Tribes Initiative, 2021). Historically, federal funding has been slow to materialize, but recent legislation has earmarked $2.5 billion to address previous funding shortfalls.[47] Therefore, tribes

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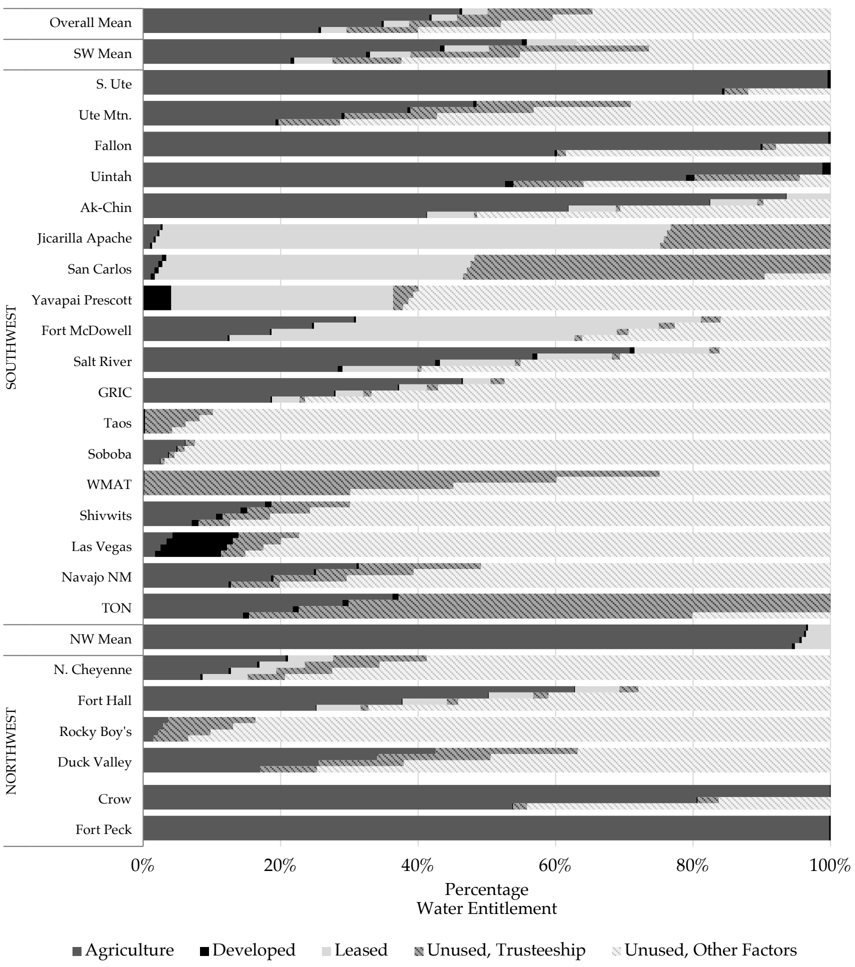
[46] Our estimates may understate the importance of land tenure because they focus only on own-parcel impacts but not on the effects on neighboring parcels. Spillovers across parcels and larger mosaics of fee simple, tribal, and allotted trust parcels may further constrain land use beyond the own-parcel effects (Leonard and Parker, 2021). Still, there appear to be important factors beyond land tenure constraining water use on some reservations.

[47] See https://www.doi.gov/pressreleases/tribes-receive-17-billion-president-bidens-bipartisan-infrastructure-law-fulfill.

Figure 6: 2012 Counterfactual Water Use Estimates



Notes: This figure depicts our estimates of counterfactual 2012 water use if the barriers associated with allotted trust and tribal trust land were removed. The estimates are obtained by adding the results of Equation 4 to Equation 3. We assume 0.25 AF/acre for developed land use. For each reservation, water use estimates depicted by each bar, from bottom to top, assume agricultural water use estimates of 2, 3, 4, and 5 AF/acre.

may be in a position to more fully use their water rights in the future.

5.2 Alternative Goals and Priorities

One possible explanation for the divergence between water entitlements and use is that our measures of water use do not fully capture the diverse priorities and goals that tribes have for water. In addition to water uses that result in extensive-margin changes in land use, tribes my pursue Winters rights for: conservation/environmental uses, increased drinking water access, agricultural intensification, off-reservation leasing, and the option of future development. We assess the evidence for whether each of these alternative uses partially or fully explain the gray areas in

Figures 5 and 6, and provide empirical evidence where data are available.

5.2.1 Conservation & Environmental Uses

Many tribes ascribe cultural significance to water and the various species it sustains and may pursue rights for these “non-use values.” However, in our sample, documented environmental water uses are almost non-existent. One reason for this is that we intentionally exclude reservations in the Pacific Northwest that pursued Winters rights specifically to support in-stream flow, because we do not expect to find major changes in agricultural land use for those reservations. Another possible reason for the limited in-stream flow activity in our data is the sometimes fraught relationship between tribes and state governments. Ultimately, in-stream flow rights are governed by state water law, and in many cases these rights must be formally transferred to the state to be valid (Boyd, 2003). Due to a long history of jurisdictional conflicts between tribes and state governments (Anderson and Parker, 2008), as well the fraught nature of federal trusteeship of many tribal resources (Leonard et al., 2020), tribes may be reluctant to rely on states to steward their rights for in-stream flow.

5.2.2 Drinking Water Access

Many homes on rural reservations like the Navajo Nation lack access to indoor plumbing, and it is possible that newfound water rights allow tribes to construct new residential water delivery systems that would not be detected by our satellite measures of land use. While expanded residential water access is a possible (and important) outcome of Winters rights that warrants further investigation in future work, we do not think it is driving the difference between water use and water entitlements identified here. In their study of post-settlement changes to water use, U.S. Bureau of Reclamation (2018) does not identify a single case where a tribe invested in new residential water infrastructure as the result of an adjudication. One reason for this is that residences on reservations tend to be dispersed and remote, driving up average delivery costs and making centralized water delivery infrastructure infeasible (U.S. Bureau of Reclamation, 2018). Finally, even if these investments were made, they would amount to a very small portion of tribes’ overall entitlements.

5.2.3 Agricultural Intensification

Another possibility is that tribes use newly acquired water rights to intensify irrigation by shifting from low-value hay and pasture to higher-value crop production without expanding farmed acreage. The results for increases in cropped acreage in columns 1 and 2 of Table A3 are small relative to those in overall agricultural land in Table 1, suggesting that this is not the case. It is also possible that reservation farmers are applying more water to crops after settlement, either to increase yields of crops they were already planting or switching production to more water intensive crops. However, the 4 and 5 AFA estimates presented in Figure 5 indicate that most reservations would still not be using their full allocation, even if they switched entirely to the most water-intensive crops such as rice, alfalfa, and sugar beets (Johnson and Cody, 2015). As a practical matter, intensification would also be limited by constraints on other factors of production as a result of credit constraints facing tribes and occupants of trust lands. For instance, Ge et al. (2020) show how investment in sprinkler irrigation systems on the Uintah and Ouray Reservation limited the production of high-value crops.

5.2.4 Off-Reservation Leasing

Leasing offers an avenue for tribes to benefit from Winters settlements in the presence of the on-reservation barriers to direct water use described above. Leasing can provide tribes with relatively swift economic return on their water entitlements — particularly given costs and delays associated with building infrastructure for on-reservation water use — while also mitigating conflicts with off-reservation users (Bovee, 2015; Nyberg, 2014).

While leasing may yet emerge as an important factor in the *future* use of Winters rights, it cannot explain the un-utilized water depicted by the gray areas in Figure 5, which already includes the share of Winters rights that are leased by each reservation. Leases account for a large share of entitlement water for some tribes, but these tribes tend to have relatively small settlements.[48] It is also unlikely there are informal or unrecorded leases between tribes and off-reservation users not captured in Figure 5 because the only incentive for off-reservation users to provide such payments would be if they were legally compelled to do so. This, in turn, would require authorization from

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[48] For example, the Yavapai-Prescott tribe leases approximately one-third of its 1,550 AF water entitlement, which is well below the average 221,000 AF entitlement volume.

Congress and, typically, Secretary of Interior approval of individual leases (Nyberg, 2014).

A related concern is that leasing may have an additional, indirect effect on water utilization through its effects on agricultural land or developed land use. This might be the case if tribes that lease their water are less likely to develop additional agriculture, for instance. To test whether leasing shapes changes in land use, we estimate a DDD model with an interaction term for reservations that lease some of their entitlement in a given year and present the results in Table A9. The results provide mixed evidence on the effect of leasing on agricultural land use. Some results suggest reservations that lease their rights do have lower increases in agricultural land use, but with coefficients that are only marginally significant and not robust to the inclusion of controls. On net, this suggests that tribes may be able to lease their water *and* develop agriculture, which is consistent with the fact that some reservations clearly do both in Figure 5.

5.2.5 Option Value

Tribes may be strategically working to obtain secure legal title to high-priority water rights now, before water resources across the West become even more scarce. In some sense, the legal strength of tribes' claims to senior water rights under the Winters doctrine is not dependent on the underlying scarcity of water. As a practical matter, however, basin-wide adjudications that are triggered by Winters cases will become more contentious and difficult to resolve as water resources become more scarce.

Because Winters rights are federally reserved and cannot be forfeited through non-use, tribes may be looking toward the long-run value of water entitlements, regardless of short-run barriers to utilization. While we cannot rule out the possibility that tribes pursue Winters rights primarily to secure future option values, two points are worth emphasizing. First, the barriers identified in Section 5.1 likely still matter insofar as they will still prevent tribal water utilization in the future if they are not eventually addressed. Second, the future benefits of off-reservation water leasing will be limited unless current policies are reformed to allow broader leasing of Winters rights.

6 Conclusion

Water right security has been fundamental to agricultural and economic development across the western United States (Hanemann, 2014; Leonard and Libecap, 2019), where water resources are fully appropriated (Grantham and Viers, 2014) and even small shifts in the distribution of water entitlements and water use can impact other water users. We show that tribal water settlements, which can result in large changes in water right entitlements, lead to an expansion of agricultural land use on reservations. This runs counter to regional water use trends of declining agricultural water use as market-based transactions redirect water away from low-value agriculture to higher value municipal, industrial, and environmental water uses (Brewer et al., 2008; Dieter, 2018).

Despite increases in agricultural land use as the result of settlement, many tribes do not yet use their full Winters water entitlements. Our causal estimates reveal that the average increase in agricultural land use for cultivated crops or pasture amounts to only 8.7%. These relatively small changes lead to correspondingly small predicted changes in *water* use in a back-of-the-envelope exercise. Our estimates, which are consistent with U.S. Bureau of Reclamation (2018) estimates where available, imply that the volume of *unused* Winters rights is 1.1–2.6 million acre-feet, with a total value of up to $1.8 billion.

Tribes have recognized this disparity and are voicing their concerns. For example, Daryl Vigil, the Chairman of the Ten Tribes Partnership in the Colorado River Basin testified before a Senate subcommittee that ”the Ten Tribes are very concerned that while they struggle to put their water to use, others with far more political clout are relying on unused tribal water rights and will seek to curtail future tribal use to protect their own uses” (Vigil, 2013). Given tribes’ vocal concerns that Winters rights will not be upheld, and ongoing water insecurity on reservations, it is unlikely that tribes are voluntarily forgoing the physical development of settlement water.

Previous literature suggests that a lack of irrigation infrastructure, land tenure issues, and barriers to investment impede tribes’ use of natural resources, and we provide suggestive evidence that this is also the case for Winters rights. If these and other barriers are eventually overcome, tribal water use will likely increase, providing tribes with options to develop agriculture, lease water, or restore environmental flows and associated amenities. As changes to reservation land and water use evolve, eventually tribes may come to control all their settlement water. Given large and growing tribal water allocations, understanding tribal water use priorities and obstacles is critical to shaping regional drought adaptation strategies and to addressing economic underdevelopment on reservations.

Tribes will also continue to play a crucial role in addressing growing water demand and variable supplies under climate change. In recent years, Colorado River Basin tribes have increased the volume of water leased to maintain water levels in Lake Mead, and tribes are emerging as critical players in Drought Contingency Planning for the Colorado River (Arizona Water Banking Authority, 2019). Hence, the "paper" Winters rights may hold considerable option value, even if they do not directly translate to "wet" water today.

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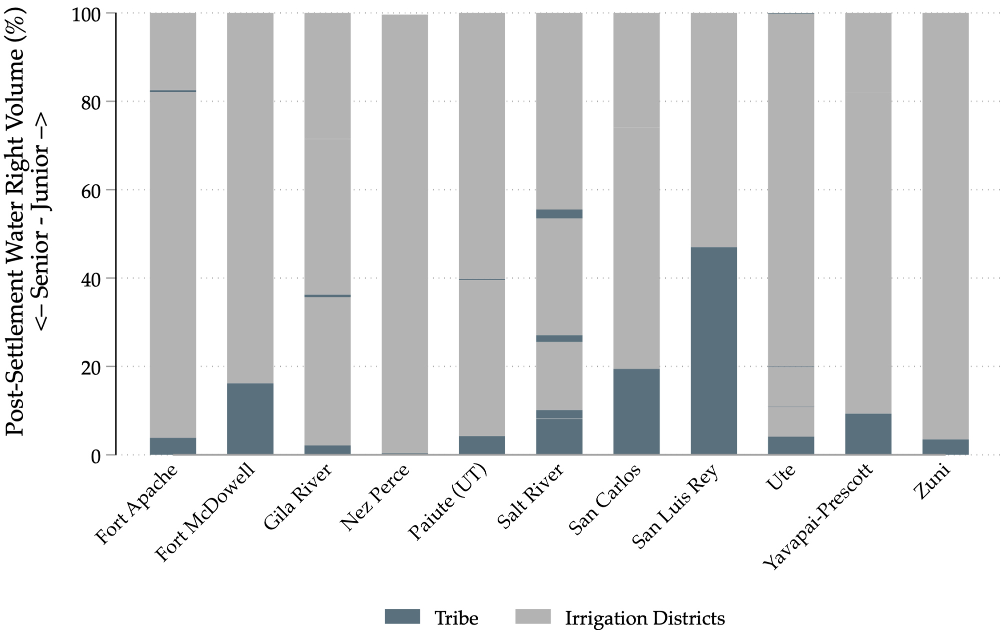
Appendix

Online appendix for *Paper Water, Wet Water, and the Recognition of Indigenous Property Rights*

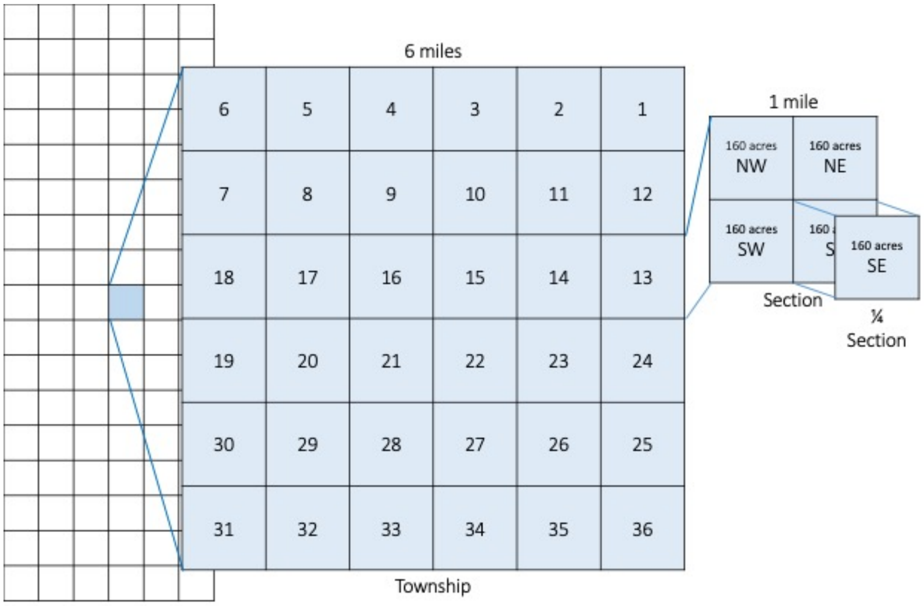
by Leslie Sanchez, Bryan Leonard, and Eric C. Edwards

Figure A1: Relative Magnitude and Priority of Tribal Water Rights



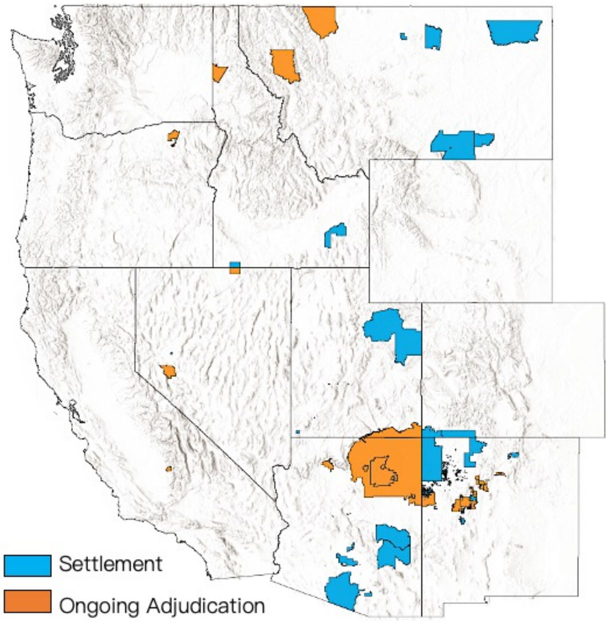
Notes: This figure depicts the relative magnitude and priority of tribal water rights after adjudication/settlement for eleven reservations using data from Sanchez (2022). Each bar is normalized to the total quantity of water rights that were resolved in a given adjudication (i.e., the total amount of water available in a basin in a "normal year"). The blue areas represent the share of tribal water rights, whereas the gray areas represent off-reservation irrigation districts (the other major party in most adjudications). The positioning of the blue shading within a bar represents the relative priority of tribal rights within a basin, where the bottom of each bar corresponds to the highest priority rights. See Sanchez (2022) for additional discussion.

Figure A2: The Public Land Survey System



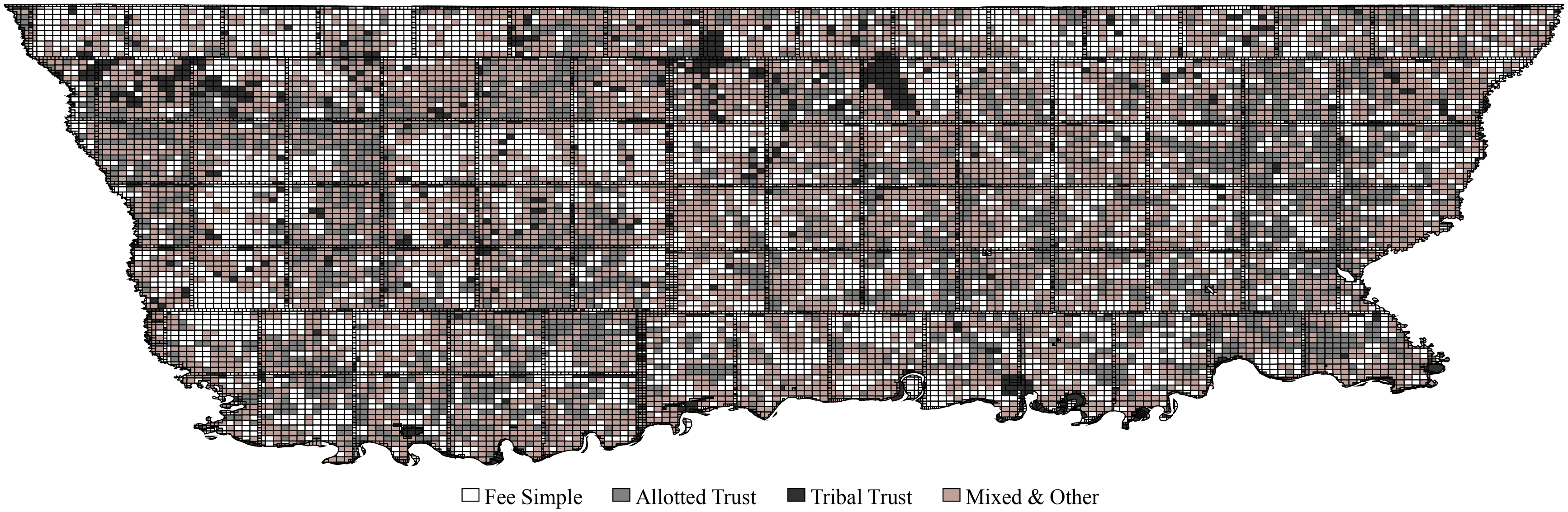
Notes: This figure depicts an example of a Public Land Survey System township unit and the section and quarter section units within each township. Each 36-square mile township can be divided into thirty-six 1-square mile sections. Each section is then divided into 160-acre quarter sections, which match the standard allotment assigned to Native American households under the Dawes Act over 1987–1934 (Carlson, 1981; Leonard et al., 2020; Dippel et al., 2020).

Figure A3: Reservations in Sample



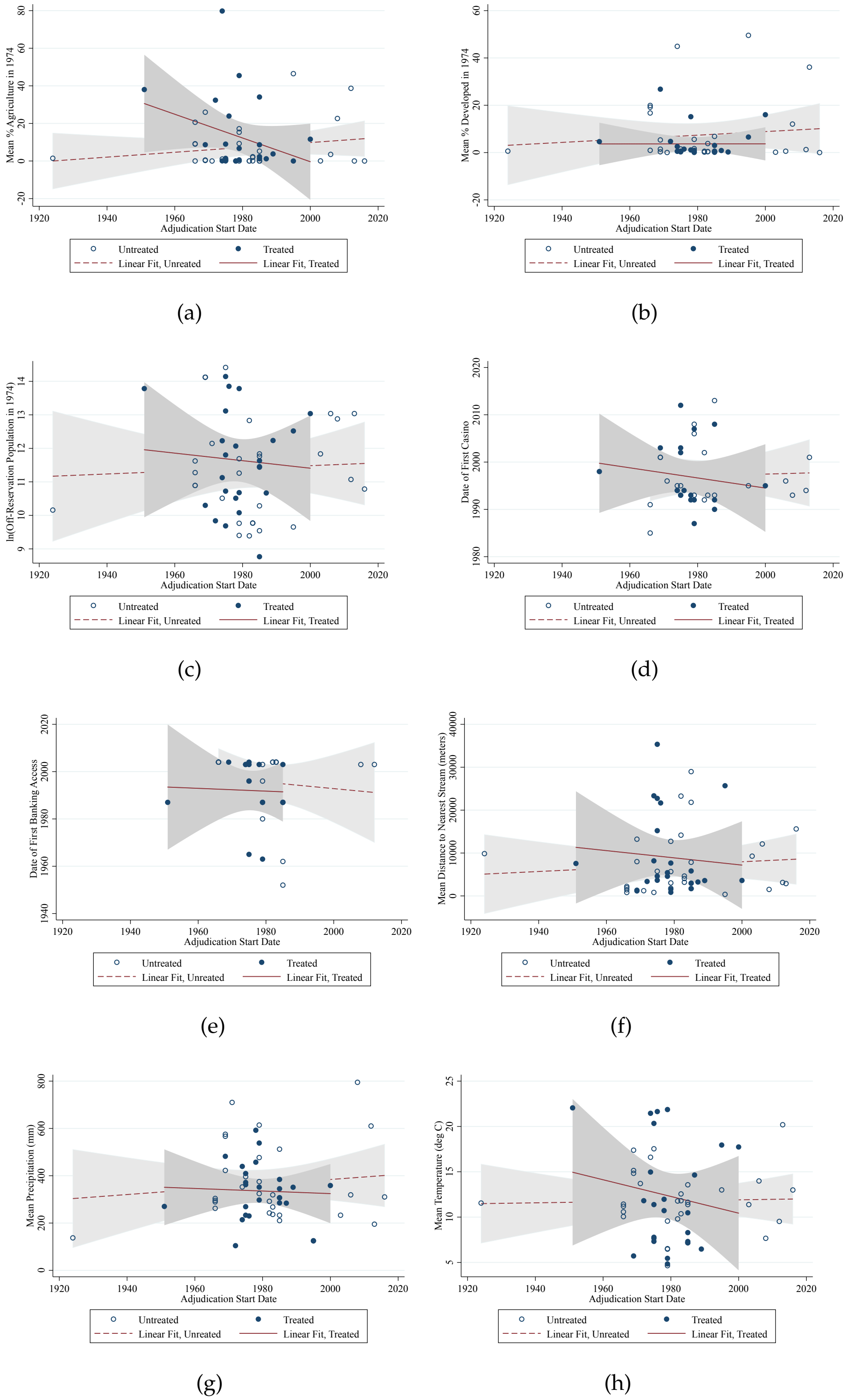
Notes: This figure depicts our sample of reservations across western states. Treatment parcels are located on reservations that achieved water settlements by 2012 (blue on the map), while untreated parcels are located on reservations with ongoing adjudications (orange on the map).

Figure A4: Land Ownership on the Fort Peck Indian Reservation



Notes: This figure depicts parcel-level land tenure data for the Fort Peck Reservation in Montana based on the data developed by (Dippel et al., 2020).

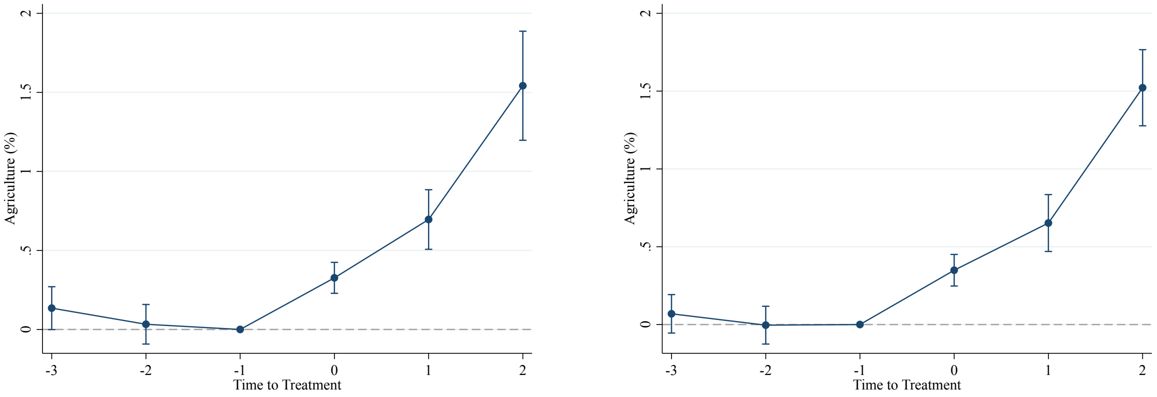
Figure A5: Adjudication Start Dates and Other Covariates



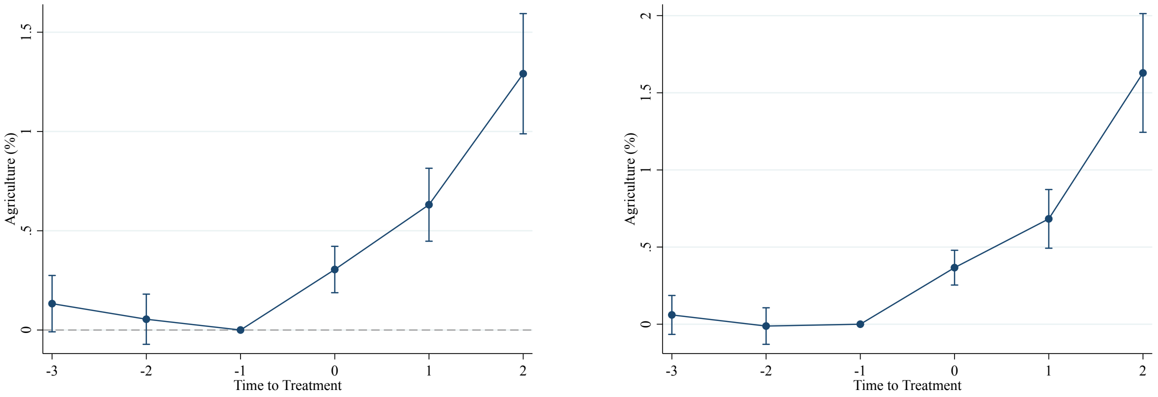
(a) (b) (c) (d) (e) (f) (g) (h)

Notes: This figure depicts scatter plots and linear correlations between reservations' adjudication start dates and several variables of interest for untreated (hollow points) vs. treated (solid points) reservations.

Figure A6: Agricultural Land Use Event Study — Alternative Specifications



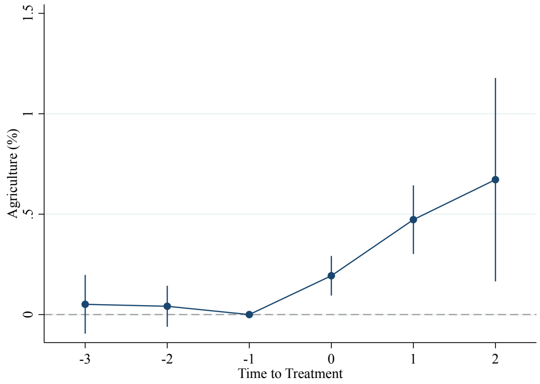
(a) Off-Res. Pop. Control (b) Casino Control



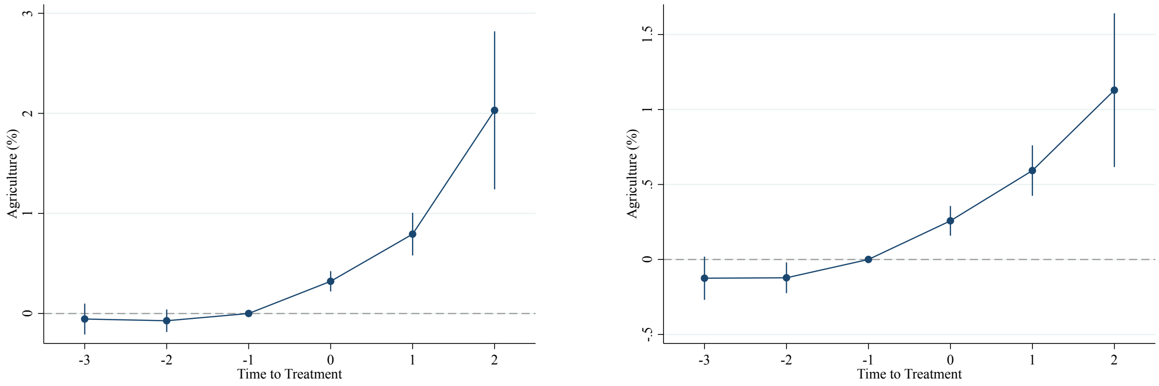
(c) Credit Control (d) All Controls

Notes: This figure depicts alternative versions of the event study estimates depicted in Figure 3 using the estimator developed by de Chaisemartin and d'Haultfoeuille (2020), implemented with the `did_multiplegt` package in Stata. The specifications in Panels (a) through (d) of the figure correspond to columns 2 through 5 of in Panel A of Table 1. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment.

Figure A7: Agricultural Land Use Event Study — Sun and Abraham (2021) Estimator

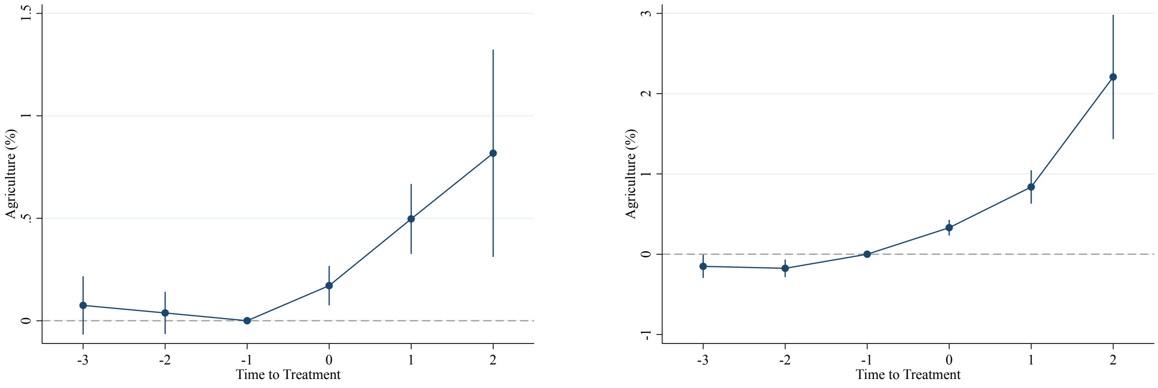


(a) No Controls



(b) Off-Res. Pop. Control

(c) Casino Control

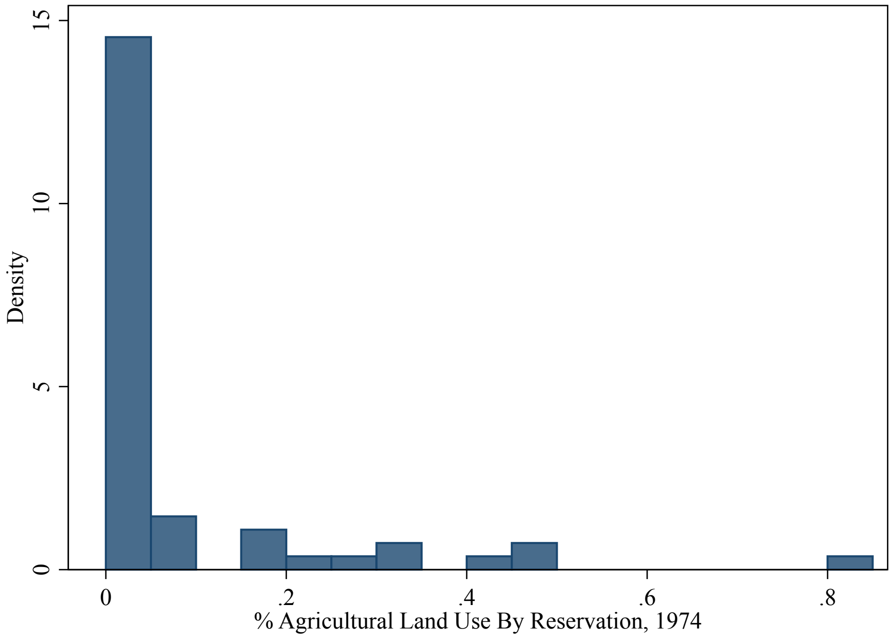


(d) Credit Control

(e) All Controls

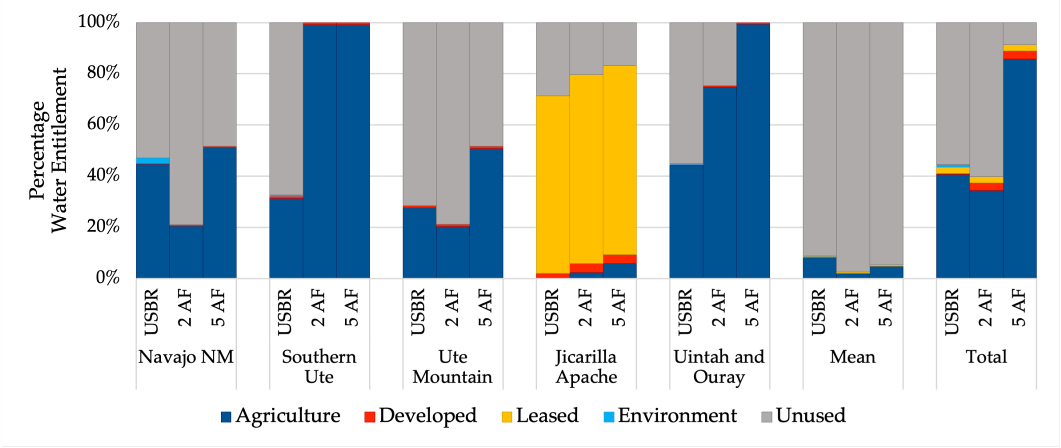
Notes: This figure depicts alternative versions of the event study estimates depicted in Figures 3 & A6 using the estimator developed by Sun and Abraham (2021), implemented with the `eventstudyinteract` package in Stata. The specifications in Panels (a) through (e) of the figure correspond to columns 1 through 5 of in Panel A of Table 1. The difference between treated and untreated groups is normalized to zero in period $t-1$, the final period before treatment. Period 0 denotes the first period in which parcels are exposed to treatment.

Figure A8: Distribution of 1974 Agricultural Land Use



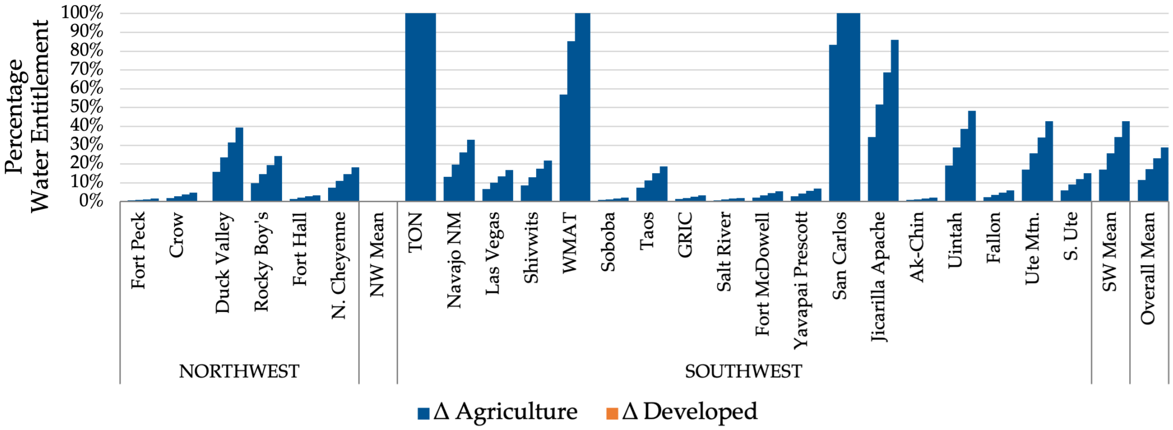
Notes: This figure depicts the distribution of 1974 agricultural land use by reservation. Each bin represents 5 percentage points (i.e., 5% agricultural land use).

Figure A9: Comparison to USBR Water Use Estimates



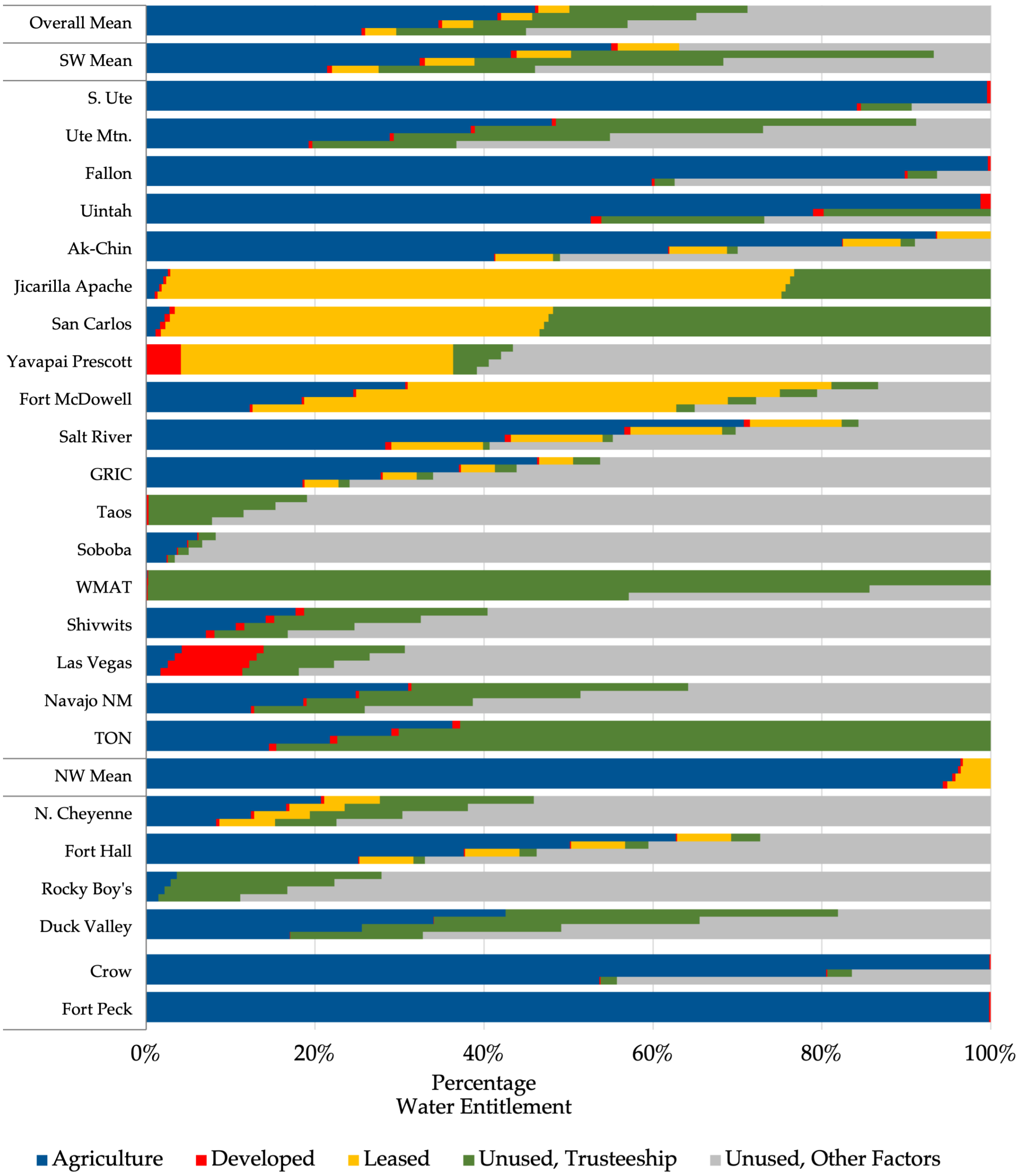
Notes: This figure depicts the US Bureau of Reclamation's estimates of water use alongside our 2 AFA and 5 AFA estimates for the five reservations where USBR estimates are available. The figure also depicts USBR-reported environmental uses of tribal water.

Figure A10: Estimated Change in Water Use Relative to Entitlements Using Long-Run Coefficients



Notes: This figure depicts estimated change in water use for each treated reservation in our sample using Equation 2 and the coefficient from the $t = 2$ time period from the de Chaisemartin and d'Haultfoeuille (2020) estimator to reflect long-run changes in land use. For each reservation, water use estimates depicted by each bar, from left to right, assume agricultural water use estimates of 2, 3, 4, and 5 AF/acre.

Figure A11: 2012 Counterfactual Water Use Estimates Using Long-Run Coefficients



Notes: This figure depicts our estimates of counterfactual 2012 water use if the barriers associated with allotted trust and tribal trust land were removed. The estimates are obtained by adding the results of Equation 4 to Equation 3, using the $t + 2$ coefficients from the de Chaisemartin and d'Haultfoeuille (2020) estimator. We assume 0.25 AF/acre for developed land use. For each reservation, water use estimates depicted by each bar, from bottom to top, assume agricultural water use estimates of 2, 3, 4, and 5 AF/acre.

Table A1: Pre-Settlement Parcel Summary Statistics (1974)

	(1) Untreated Group	(2) Settlement Parcels	(3) Settlement - Untreated
% Agriculture	4.470	10.631	6.16
	(18.716)	(27.690)	(0.904)
% Development	1.429	0.704	-0.724
	(10.181)	(6.053)	(0.351)
Avg. Soil PI	6.568	8.046	1.479
	(4.566)	(4.369)	(0.190)
Avg. Elevation	1,579.532	1,539.476	-40.055
	(440.810)	(697.382)	(27.057)
Ruggedness	12.526	13.952	1.427
	(18.584)	(18.491)	(0.535)
Distance to Stream	14,903.496	9,472.705	-5,430.79
	(14,023.704)	(12,244.000)	(627.587)
Fee Simple	0.091	0.153	0.062
	(0.288)	(0.360)	(0.010)
Allotted Trust	0.068	0.136	0.068
	(0.252)	(0.343)	(0.009)
Tribal Trust	0.717	0.599	-0.118
	(0.451)	(0.490)	(0.018)
BIA Project	0.042	0.599	0.557
	(0.200)	(0.490)	(0.018)
Observations	130,221	151,816	282,037

Notes: This table presents baseline (1974) summary statistics for parcels that are always untreated (column 1), or eventually treated (column 2), and the difference between the two (column 3). Standard errors are clustered by township and reported in parentheses.

Table A2: Time-Varying Summary Statistics

		(1) Unteated Group	(2) Settlement Parcels	(3) Settlement - Untreated	(4)
1974	1(Post Settlement)	0.000	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
	Off-Res. Pop.	135263.359	312103.531	176840.156	289751.219
		(146437.703)	(362690.125)	(13,125.346)	(17,020.389)
	1(Has Casino)	0.000	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
	1(Tribal Lending Institution)	0.498	0.266	-0.232	-0.066
		(0.500)	(0.442)	(0.024)	(0.025)
1982	1(Post Settlement)	0.000	0.001	0.001	0.003
		(0.000)	(0.037)	(0.001)	(0.001)
	Off-Res. Pop.	161187.484	447799.125	286611.625	451829.156
		(201334.250)	(553890.562)	(19,593.615)	(26,537.297)
	1(Has Casino)	0.000	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
	1(Tribal Lending Institution)	0.581	0.266	-0.315	-0.178
		(0.493)	(0.442)	(0.023)	(0.026)
1992	1(Post Settlement)	0.000	0.197	0.197	0.191
		(0.000)	(0.398)	(0.014)	(0.015)
	Off-Res. Pop.	192360.422	564141.750	371781.312	613581
		(271260.469)	(771019.688)	(27,202.996)	(36,851.465)
	1(Has Casino)	0.030	0.187	0.157	0.128
		(0.171)	(0.390)	(0.015)	(0.016)
	1(Tribal Lending Institution)	0.682	0.310	-0.372	-0.278
		(0.466)	(0.463)	(0.023)	(0.026)
2002	1(Post Settlement)	0.000	0.675	0.675	0.61
		(0.000)	(0.469)	(0.016)	(0.019)
	Off-Res. Pop.	233258.828	756565.812	523306.969	869115.062
		(316746.750)	(1.098e+06)	(37,643.793)	(52,895.324)
	1(Has Casino)	0.208	0.486	0.278	0.395
		(0.406)	(0.500)	(0.023)	(0.023)
	1(Tribal Lending Institution)	0.724	0.432	-0.292	-0.192
		(0.447)	(0.495)	(0.024)	(0.022)
2012	1(Post Settlement)	0.000	1.000	1.000	1.000
		(0.000)	(0.000)	(0.000)	(0.000)
	Off-Res. Pop.	270889.719	954301.562	683411.812	1.12E+06
		(374084.844)	(1.392e+06)	(47,353.766)	(67,011.602)
	1(Has Casino)	0.331	0.732	0.401	0.418
		(0.471)	(0.443)	(0.023)	(0.018)
	1(Tribal Lending Institution)	0.875	0.656	-0.22	-0.073
		(0.330)	(0.475)	(0.021)	(0.014)
	Observations	112,254	144,933	257,187	257,187
State FE					✓

Notes: This table presents year-specific summary statistics of time-varying reservation-level variables for parcels that are always untreated (column 1), or eventually treated (column 2), and the difference between the two (columns 3 and 4). Column 3 shows raw comparisons whereas column 4 shows within-state comparisons. Standard errors are clustered by township and reported in parentheses.

Table A3: Alternative Outcome Variables

	(1)	(2)	(3)	(4)	(5)	(6)
	% Cultivated Crops		1(% Agriculture > 0)		% Development	
Panel A:	*de Chaisemartin & D'Haultfoeuille (2020)*					
Post Settlement	0.222 (0.059)	0.226 (0.086)	0.0186 (0.0024)	0.0199 (0.0025)	-0.042 (0.101)	-0.081 (0.085)
Panel B:	*Callaway & Sant'Anna (2020)*					
Post Settlement	0.140 (0.049)	0.118 (0.158)	0.0101 (0.0014)	0.0237 (0.0041)	0.095 (0.142)	-0.282 (0.233)
Panel C:	*Two-Way Fixed Effects*					
Post Settlement	0.221 (0.068)	0.349 (0.068)	0.0060 (0.0013)	0.0091 (0.0015)	-0.052 (0.163)	-0.077 (0.117)
Observations	1,410,185	1,410,182	1,410,185	1,410,182	1,410,185	1,410,182
Adjusted R-squared (TWFE)	0.98	0.98	0.948	0.948	0.888	0.888
Parcel Fixed Effects	✓	✓	✓	✓	✓	✓
Off-Reservation Population		✓		✓		✓
1(Casino)		✓		✓		✓
1(Tribal Lending Institution)		✓		✓		✓

Notes: This table presents estimates for the effect of Winters settlements on a variety of alternative outcomes, using the specifications from column 1 and column 5 of Table 1. In columns 1 and 2, the dependent variable is the percentage of a parcel that is covered by cultivated crops, a measure that excludes pasture land. In columns 3 and 4, the dependent variable is a dummy variable equal to one if a parcel has any agriculture. In columns 5 and 6, the dependent variable is the percentage of a parcel covered by developed pixels. Panel A uses the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and implemented with the `did_multiplegt` Stata package with two leads and two lags of treatment. Panel B uses the estimator proposed by Callaway and Sant'Anna (2021) and implemented with the `csdid` package in Stata. Panel C presents traditional TWFE estimates obtained via OLS. Panels A and C include state-by-year fixed effects, whereas Panel B uses pooled year fixed effects due to limitations of the `csdid` package. Standard errors are clustered by PLSS township (a 6×6-mile square containing 144 parcels) and reported in parentheses.

Table A4: The Impact of Winters Settlements, Additional Robustness

	(1)	(2)	(3)	(4)	(5)	(6)
			Y = % Agriculture			
Panel A:						
			de Chaisemartin & D'Haultfoeuille (2020)			
Post Settlement	0.699	0.702	0.699	0.707	0.268	0.479
	(0.107)	(0.085)	(0.106)	(0.099)	(0.081)	(0.089)
Panel B:						
			Callaway & Sant'Anna (2020)			
Post Settlement	0.381	4.343	0.547	NA*	NA*	NA*
	(0.073)	(0.932)	(0.102)			
Panel C:						
			Two-Way Fixed Effects			
Post Settlement	0.433	0.784	0.440	0.785	0.243	0.399
	(0.085)	(0.103)	(0.087)	(0.102)	(0.069)	(0.067)
Observations	928,840	928,840	928,840	928,840	1,410,185	1,410,182
Adjusted R-squared (TWFE)	0.972	0.972	0.972	0.972	0.979	0.979
Parcel Fixed Effects	✓	✓	✓	✓	✓	✓
Off-Reservation Population		✓		✓		✓
1(Casino)		✓		✓		✓
1(Tribal Lending Institution)		✓		✓		✓
Groundwater Sample	✓	✓	✓	✓		
Groundwater Control			✓	✓		
Start Date-by-Year FE					✓	✓

Notes: This table presents difference-in-difference estimates for the effect of Winters settlements based on the model in Equation 1 and columns 1 and 5 of Table 1, subject to several alternative specifications. Columns 1 and 2 restrict the sample to the subset of 19 reservations for which we are able to obtain complete depth-to-groundwater data (the control is not included in columns 1 and 2, to focus on the effect of sample restrictions). To construct this variable, we identify all wells in the USGS data available at `https://nwis.waterdata.usgs.gov/usa/nwis/gwlevels` in counties that overlap each reservation. We then take the average depth-to-groundwater table across all wells associated with a given reservation in each year. This exercise omits 32 reservations for which we are not able to obtain groundwater estimates across all five years of our data. Columns 3 and 4 include the control for depth-to-groundwater table. Columns 5 and six replace state-by-year fixed effects with "start date-by-year fixed effects." To construct these fixed effects, we group reservations into seven categories based on when they *began* adjudicating their water rights and then allow for differential year fixed effects across each of these seven groups. We are unable to use the Callaway and Sant'Anna (2021) estimator for this exercises because it does not allow group-specific time fixed effects. Panel A uses the estimator proposed by de Chaisemartin and d'Haultfoeuille (2020) and implemented with the `did_multiplegt` Stata package with two leads and two lags of treatment. Panel B uses the estimator proposed by Callaway and Sant'Anna (2021) and implemented with the `csdid` package in Stata. Panel C presents traditional TWFE estimates obtained via OLS. Panels A and C include state-by-year fixed effects, whereas Panel B uses pooled year fixed effects due to limitations of the `csdid` package. Standard errors are clustered by PLSS township (a 6×6-mile square containing 144 parcels) and reported in parentheses. * The `csdid` estimator did not converge for the Columns 5 specification, which is why this coefficient is omitted.

Table A5: Differential Impacts by 1974 Land Use

	(1)	(2)	(3)	(4)	(5)
	Y = % Agriculture				
Panel A:					
Post Settlement	0.160	0.249	0.348	0.168	0.366
	(0.057)	(0.069)	(0.064)	(0.059)	(0.071)
Post Settlement X (Reservation Ag 1974 > 5%)	0.135	0.112	0.0004	0.093	-0.015
	(0.146)	(0.148)	(0.152)	(0.161)	(0.165)
Adjusted R-squared	0.979	0.979	0.979	0.979	0.979
Panel B:					
Post Settlement	0.180	0.264	0.348	0.191	0.367
	(0.056)	(0.064)	(0.059)	(0.059)	(0.066)
Post Settlement X (Reservation Ag 1974 > 10%)	0.106	0.098	-0.001	0.039	-0.024
	(0.169)	(0.167)	(0.174)	(0.201)	(0.198)
Adjusted R-squared	0.979	0.979	0.979	0.979	0.979
Panel C:					
Post Settlement	0.157	0.250	0.320	0.163	0.341
	(0.060)	(0.067)	(0.062)	(0.062)	(0.067)
Post Settlement X (Reservation Ag 1974 > 20%)	0.229	0.163	0.109	0.178	0.082
	(0.210)	(0.217)	(0.215)	(0.239)	(0.241)
Observations	1,504,140	1,504,140	1,504,140	1,504,140	1,504,140
Adjusted R-squared (TWFE)	0.979	0.979	0.979	0.979	0.979
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents estimates of the differential change in agricultural land use on reservations with differing levels of pre-settlement agriculture in 1974 using TWFE. Panel A includes an interaction term for reservations with greater than 5% of their total area devoted to agriculture in 1974–the baseline effect in Panel A is therefore the increase in agricultural land use on reservations with less than 5% agricultural land use in 1974. Panel B uses a 10% cutoff for the interaction term, whereas Panel C uses a 20% cutoff. Standard errors are clustered by township and reported in parentheses.

Table A6: Differential Impacts for Reservations with BIA Projects

	(1)	(2)	(3)	(4)	(5)
			Y = % Agriculture		
Panel A:					
			de Chaisemartin & D'Haultfoeuille (2020)		
Post Settlement (No BIA Project)	-0.063	0.072	0.161	-0.067	0.220
	(0.052)	(0.078)	(0.049)	(0.057)	(0.084)
Post-Settlement (BIA Project)	0.891	0.907	0.843	0.894	0.857
	(0.069)	(0.067)	(0.079)	(0.076)	(0.085)
Panel B:					
			Callaway & Sant'Anna (2020)		
Post Settlement (No BIA Project)	-0.356	-0.204	-0.312	-0.663	-0.121
	(0.065)	(0.154)	(0.065)	(0.102)	(0.183)
Post-Settlement (BIA Project)	0.639	0.634	0.633	0.833	0.880
	(0.082)	(0.079)	(0.082)	(0.109)	(0.106)
Panel C:					
			Two-Way Fixed Effects		
Post Settlement	-0.0932	-0.00985	0.106	-0.0934	0.122
	(0.069)	(0.069)	(0.071)	(0.071)	(0.074)
Post Settlement X BIA Project	0.615	0.572	0.439	0.616	0.449
	(0.114)	(0.115)	(0.126)	(0.117)	(0.126)
Observations	1,410,185	1,410,182	1,410,185	1,410,185	1,410,182
Adjusted R-squared (TWFE)	0.979	0.979	0.979	0.979	0.979
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents DiD estimates separately for parcels on reservations that do not have a BIA irrigation project, and for parcels on reservations that do have a BIA irrigation project using a difference-in-difference-in-difference model:

$$y_{irt} = \beta_1 PostSettlement_{rt} + \beta_B PostSettlement_{rt} \times BIA_r + +\beta_2 X_r t + \vec{\lambda}_i + \vec{\tau}_t + \varepsilon_{irt}$$

where BIA_r is an indicator that is equal to one for parcels on reservations with a BIA project. β_1 is the estimated effect of Winters rights on reservations without a project, the omitted group, and β_B reports the difference in this effect for parcels on reservations with a project. All other parameters are defined as in Equation 1. The omitted category for the baseline difference is reservations with no BIA project. Panel A presents estimators specified by de Chaisemartin and d'Haultfoeuille (2020), Panel B presents estimators specified by Callaway and Sant'Anna (2021), and Pancel C presents estimates obtained using two-way fixed effects. Standard errors are clustered by township and reported in parentheses.

Table A7: Differential Impacts by Land Tenure Class: Agriculture

	(1)	(2)	(3)	(4)	(5)
	Y = % Agriculture				
Panel A:					
	de Chaisemartin & D'Haultfoeuille (2020)				
Post Settlement (Fee Simple)	0.825	0.876	0.649	0.840	0.718
	(0.098)	(0.132)	(0.129)	(0.109)	(0.171)
Post Settlement (Allotted)	0.763	0.795	0.621	0.714	0.594
	(0.262)	(0.64)	(0.239)	(0.261)	(0.241)
Post Settlement (Tribal)	0.338	0.361	0.410	0.333	0.409
	(0.097)	(0.099)	(0.105)	(0.096)	(0.107)
Panel B:					
	Callaway & Sant'Anna (2020)				
Post Settlement (Fee Simple)	0.725	0.721	0.975	0.994	0.811
	(0.190)	(0.180)	(0.156)	(0.238)	(0.236)
Post Settlement (Allotted)	-0.007	-0.047	0.167	-0.254	-0.022
	(0.222)	(0.180)	(0.176)	(0.442)	(0.279)
Post Settlement (Tribal)	0.199	0.531	0.200	0.249	0.526
	(0.044)	(0.216)	(0.044)	(0.098)	(0.151)
Panel C:					
	Two-Way Fixed Effects				
Post Settlement (Fee Simple)	0.908	0.928	0.947	0.905	0.953
	(0.148)	(0.148)	(0.146)	(0.147)	(0.146)
Post Settlement X Allotted	-0.727	-0.728	-0.705	-0.725	-0.712
	(0.161)	(0.161)	(0.161)	(0.159)	(0.159)
Post Settlement X Tribal	-0.905	-0.887	-0.814	-0.903	-0.824
	(0.148)	(0.150)	(0.154)	(0.151)	(0.155)
Observations	1,244,285	1,244,282	1,244,285	1,244,285	1,244,282
Adjusted R-squared (TWFE)	0.980	0.980	0.980	0.980	0.980
p-value, Fee + Allotted (TWFE)	0.196	0.146	0.0743	0.198	0.0765
p-value, Fee + Tribal (TWFE)	0.965	0.536	0.0278	0.966	0.0421
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents estimates of the difference-in-difference-in-difference model:

$$y_{irt} = \beta_F PostSettlement_{rt} + \beta_A PostSettlement_{rt} \times Allotted_i$$

$$+ \beta_T PostSettlement_{rt} \times Tribal_i + \beta_2 X_r t + \vec{\lambda}_i + \vec{\tau}_t + \varepsilon_{irt}$$

where $Allotted_i$ is an indicator that is equal to one for allotted trust parcels and $Tribal_i$ is an indicator that is equal to one for tribal trust parcels. β_F is the estimated effect of Winters rights on fee simple parcels, the omitted group, and β_A and β_T report the difference in this effect for allotted and tribal parcels, respectively. All other parameters are defined as in Equation 1. The omitted category for the baseline difference is fee simple land tenure. Panels A and B present alternative DiD estimates for each group separately using the methods proposed by de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2021), which cannot be used directly to estimate a DDD model. Standard errors are clustered by township and reported in parentheses.

Table A8: Differential Impacts by Land Tenure Class: Development

	(1)	(2)	(3)	(4)	(5)
			Y = % Development		
Panel A:					
			de Chaisemartin & D'Haultfoeuille (2020)		
Post Settlement (Fee Simple)	-0.029	-0.172	-0.042	-0.022	-0.181
	(0.027)	(0.119)	(0.033)	(0.026)	(0.115)
Post Settlement (Allotted)	0.091	0.061	0.096	0.097	0.066
	(0.057)	(0.049)	(0.057)	(0.056)	(0.047)
Post Settlement (Tribal)	-0.122	-0.117	-0.069	-0.121	-0.077
	(0.145)	(0.133)	(0.109)	(0.143)	(0.123)
Panel B:					
			Callaway & Sant'Anna (2020)		
Post Settlement (Fee Simple)	-0.088	-0.087	-0.019	-0.084	-0.053
	(0.069)	(0.070)	(0.046)	(0.059)	(0.057)
Post Settlement (Allotted)	-0.100	0.002	-0.054	-0.290	0.110
	(0.137)	(0.074)	(0.113)	(0.286)	(0.106)
Post Settlement (Tribal)	0.196	-0.049	0.193	0.062	-0.209
	(0.226)	(0.648)	(0.226)	(0.246)	(0.337)
Panel C:					
			Two-Way Fixed Effects		
Post Settlement (Fee Simple)	-0.0255	-0.0617	-0.0239	0.0524	0.0292
	(0.1269	(0.132)	(0.112)	(0.109)	(0.098)
Post Settlement X Allotted	-0.134	-0.132	-0.133	-0.202	-0.19
	(0.112)	(0.111)	(0.104)	(0.129)	(0.123)
Post Settlement X Tribal	-0.0538	-0.088	-0.0499	-0.129	-0.126
	(0.089)	(0.092)	(0.058)	(0.118)	(0.084)
Observations	1,244,285	1,244,282	1,244,285	1,244,285	1,244,282
Adjusted R-squared (TWFE)	0.89	0.89	0.89	0.89	0.89
p-value, Fee + Allotted (TWFE)	0.433	0.330	0.365	0.450	0.335
p-value, Fee + Tribal (TWFE)	0.691	0.465	0.591	0.697	0.506
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents estimates of the difference-in-difference-in-difference model presented using the methods proposed by de Chaisemartin and d'Haultfoeuille (2020) in Panel A and Callaway and Sant'Anna (2021) in Panel BTable A7, and using TWFE in Panel C. The omitted category for the baseline difference is fee simple land tenure. Panels A and B present alternative DiD estimates for each group separately using the methods proposed by de Chaisemartin and d'Haultfoeuille (2020) and Callaway and Sant'Anna (2021), which cannot be used directly to estimate a DDD model. Standard errors are clustered by township and reported in parentheses.

Table A9: Differential Impacts by Leasing Status

	(1)	(2)	(3)	(4)	(5)
Panel A:					
	Y = % Agriculture				
Post Settlement	0.276	0.364	0.392	0.263	0.413
	(0.068)	(0.076)	(0.066)	(0.064)	(0.069)
Post Settlement X Lease	-0.272	-0.285	-0.197	-0.245	-0.203
	(0.156)	(0.156)	(0.152)	(0.152)	(0.156)
Adjusted R-squared	0.979	0.979	0.979	0.979	0.979
p-value (Post Settlement + Post Settlement X Lease)	0.976	0.57	0.182	0.902	0.137
Panel B:					
	Y = % Development				
Post Settlement	-0.158	-0.239	-0.160	-0.121	-0.178
	(0.141)	(0.144)	(0.104)	(0.127)	(0.101)
Post Settlement X Lease	0.428	0.441	0.427	0.351	0.390
	(0.239)	(0.239)	(0.232)	(0.245)	(0.240)
Adjusted R-squared	0.888	0.888	0.888	0.888	0.888
p-value (Post Settlement + Post Settlement X Lease)	0.367	0.481	0.300	0.454	0.411
Observations	1,504,140	1,504,140	1,504,140	1,504,140	1,504,140
Parcel Fixed Effects	✓	✓	✓	✓	✓
Off-Reservation Population		✓			✓
1(Casino)			✓		✓
1(Tribal Lending Institution)				✓	✓

Notes: This table presents estimates of the difference-in-difference-in-difference model:

$$y_{irt} = \beta_N PostSettlement_{rt} + \beta_L PostSettlement_{rt} \times Lease_{rt} + \beta_2 X_r t + \vec{\lambda}_i + \vec{\tau}_t + \varepsilon_{irt}$$

where $Lease_{rt}$ is equal to one in post-settlement year if a parcel lies on a reservation that leases some or all of its settlement water (and a value of 0 for parcels on reservations that have not settled yet or do not lease settlement water). All other variables are defined as in Table 1. In this framework, β_N represents the effect of a Winters settlement on non-leasing reservations (the omitted group) and β_L represents the difference in the effect of settlement for reservations that lease some portion of their water rights back to off-reservation users. As before, we estimate the model using TWFE. Because $Lease_{rt}$ varies over time and is only non-zero for treated reservations, we are not able to construct separate robust DiD estimates for leasing vs. non-leasing reservations was we did for BIA projects and land tenure. The omitted category for the baseline difference is reservations that do not lease any water.