Earth's Future

Supporting Information for

Two-Way Option Contracts that Facilitate Adaptive Water Reallocation in the Western United States

Zachary M. Hirsch[1,2], Harrison B. Zeff [1,2], Rohini S. Gupta[3], Chris R. Vernon[4], Patrick M. Reed[3], and Gregory W. Characklis[1,2]

[1] Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA 27599

[2] Center on Financial Risk in Environmental Systems, Gillings School of Global Public Health and UNC Institute for the Environment, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA 27599

[3] Department of Civil and Environmental Engineering, School of Engineering, Cornell University, Ithaca, NY, USA 14853

[4] Pacific Northwest National Laboratory, Richland, WA, USA 99354

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Text S1.

StateMod inputs are written in large, uniquely formatted text files, making it a challenge to analyze the model inputs/outputs. This analysis takes advantage of StateModify, a python-based package which converts select StateMod files into a 'parquet', a file format that can be easily exported to a dataframe which allows for a streamlined analysis of the model's input and output files. The StateModify generated parquet files were used to analyze historical data which led to re-writing the Fortran inputs to StateMod used in the adapted SPRB StateMod version (Table S1), this includes updating the transbasin distribution of water through StateMod's nodal network, as well as updating municipal and irrigation demands. Once the adapted SPRB StateMod model was run, the StateMod output file to parquet process was used for further data analysis and visualization of the model's results.

Table S1. *Adaptations to the South Platte StateMod model (SP2016_H)*

StateMod input file	Adaptation
SP2016.ddr	-Direct diversion rights are equal to the decreed amounts in 2012.
SP2016.ddm	-Transbasin diversion deliveries are representative of those in recent years. -Municipal indoor and outdoor demands are reflective of demands in recent years. -Irrigator demands are reflective of deliveries in 2010.
SP2016.rer	-Reservoir rights are equal to the decreed amounts in 2012.
SP2016.tar	-Reservoir maximum contents are equal to reservoir capacities in 2012.
SP2016.weh	-Groundwater diversions are equal to those in 2012.
SP2016.ipy	-Irrigation efficiencies, acreages are representative of those in 2010.
SP2016.ddc	-Irrigation water requirements are representative of those in 2010.
SP2016.opr	-Operating rules represent the source, destination, priority, rule types of those in 2012 for the current rights regime (or 1971 for the historical rights regime)
SP2016_H.rsp	-Updated the nomenclature for the adapted input files to run StateMod.

Table S2. *Marginal Net Benefits of Production per hectare in the State of Colorado along with the total hectares of each crop in the Northern Water District* (Colorado State University Extension, 2019)

Crop Type	**Marginal Net Benefit of Production/hectacre (acre) ($) ($MNB_{crop}$)**	**Total Hectares (acres) in Northern Water District**
Grass Pasture	73.2 (181)	56,464 (139,527)
Alfalfa	176.6 (436.3)	48,308 (119,372)
Corn Grain	142.7 (352.5)	71,430 (176,508)
Small Grains	30.4 (75)	7,350 (18,162)
Sorghum Grain	85.8 (212.2)	310 (766)
Sugar Beets	201.3 (497.5)	4,622 (11,422)
Dry Beans	106.8 (263.9)	1,912 (4,725)
Potatoes	2 (5)	264 (653)
Sunflower	159 (392.9)	1,668 (4,121)
Vegetables	208.6 (515.4)	287 (709)
Snap Beans	208.6 (515.4)	5 (12)
Spring Grain	62.1 (153.4)	173 (428)
Fall Wheat	62.1 (153.4)	15,087 (37,281)

Text S2.

Option contracts include two parts, the fixed option payment made at regular intervals (in this case annually), and an option exercise fee paid when the option is exercised or ‘called’. The exercise fee is a pre-determined price per cubic-meter (or acre-foot) that is only paid if the option is exercised, and the water transferred. The fixed option purchase price is paid for by the user in order to compensate the seller for the risk that they take when/if the contract is exercised and is accepted by the buyer for the flexibility and security the option provides. The option is triggered, such that the buyer has the right (but not the obligation) to exercise the option when a specified CBI index threshold is crossed. In this work, the TWO is triggered in dry years when the CBI drops below 700, and in wet years when the CBI > 800. The fixed option fee is calculated using an option-pricing model, the Wang Transform, an actuarial method for pricing risk (Wang, 2000) and is based on the frequency and magnitude of the value of the transferred water. The distribution of option fees used to price out the risk-transformed option fee is equal to the marginal value of water as measured by simulated lease prices from a given pricing scenario minus the agreed upon exercise fee, where:

$$Option\ Fee = \sum V_{y,s,crop} \cdot (MV_{y,s,crop} - Exercise\ Fee) \quad \text{(A1)}$$

Where, $Option\ Fee$ = \$; $V_{y,s,crop}$ = volume of water to be re-allocated in a given year (AF); $MV_{y,s,crop}$ = simulated lease price for water (\$/m^3(AF)); $Exercise\ Fee$ = \$/m^3(AF)

The Wang transform takes a standard normal distribution of option fees (equation A1) and the 'Sharpe Ratio', the market price of risk to create a risk-neutral distribution. In this way, the market price of risk is attached solely to the option fee.

$$S^*(x) = \phi[\phi^{-1}(S(x)) + \gamma] \tag{A2}$$

Where, $S^*(x)$ = risk neutral probability distribution; $S(x)$ = normal probability distribution of losses; ϕ = cumulative normal distribution; ϕ^{-1} = cumulative normal distribution; γ = Sharpe ratio

The risk transformed option fee is then derived as the sum of the unique option fee values multiplied by the risk neutral probability distribution, divided by the maximum amount of water re-allocated in any year (Equation A3).

$$Risk\ Transformed\ Option\ Fee = \frac{\sum\left(S^*(x)\right)\cdot(Option\ Fee)}{W_{max}} \tag{A3}$$

Where, $Risk\ Transformed\ Option\ Fee$ = \$; $S^*(x)$ = risk neutral probability distribution; $Option\ Fee$ = \$; W_{max} = yearly maximum water re-allocated across the simulation

The resulting combination of the risk transformed option fee and pre-determined exercise fee equates to the total option cost (Equation A4).

$$Total\ Option\ Cost = Risk\ Transformed\ Option\ Fee + Exercise\ Fee \quad \text{(A4)}$$

Where, $Total\ Option\ Cost$ = total amount paid in an 'exercised year' ($);
$Risk\ Transformed\ Option\ Fee$ = yearly fee paid ($); $Exercise\ Fee$ = pre-arranged price for water in an exercised year ($)

The two-way option is built as two call options, thus the process described here is repeated in both wet and dry years.

While results are shown with selected exercise fees, this modeling framework can be re-operated with different selected exercise fees, differing the amount paid yearly through the option fee. Yearly option fees and exercise fees are inversely related, such that a larger exercise fee will equate to a lower yearly option cost and vice versa, as shown in Figure S1 and Figure S2.

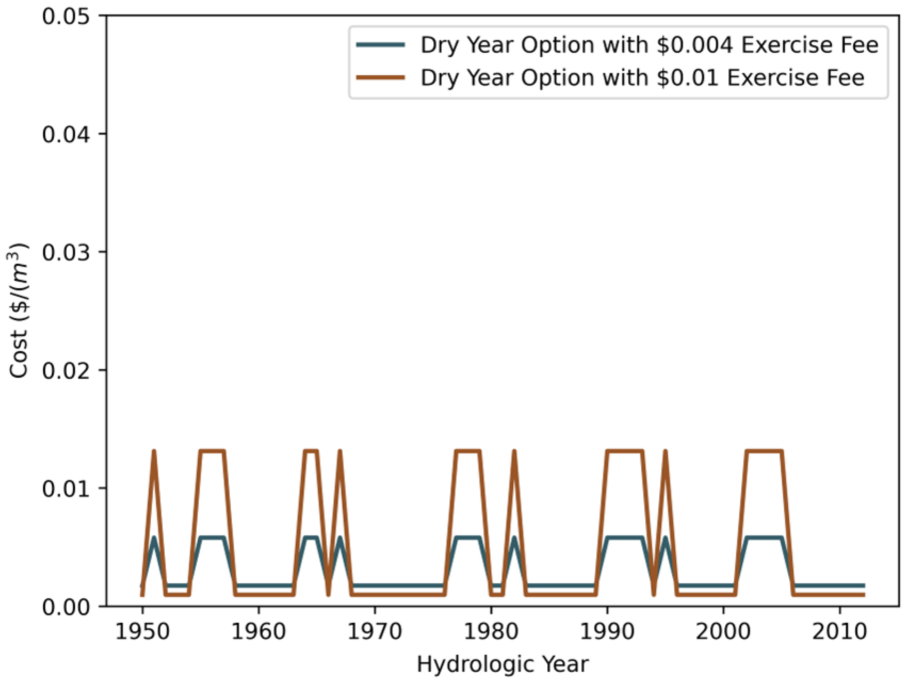

Figure S1. *Dry year pricing of the two-way option with varying exercise fees in the current rights regime under pricing scenario 1.*

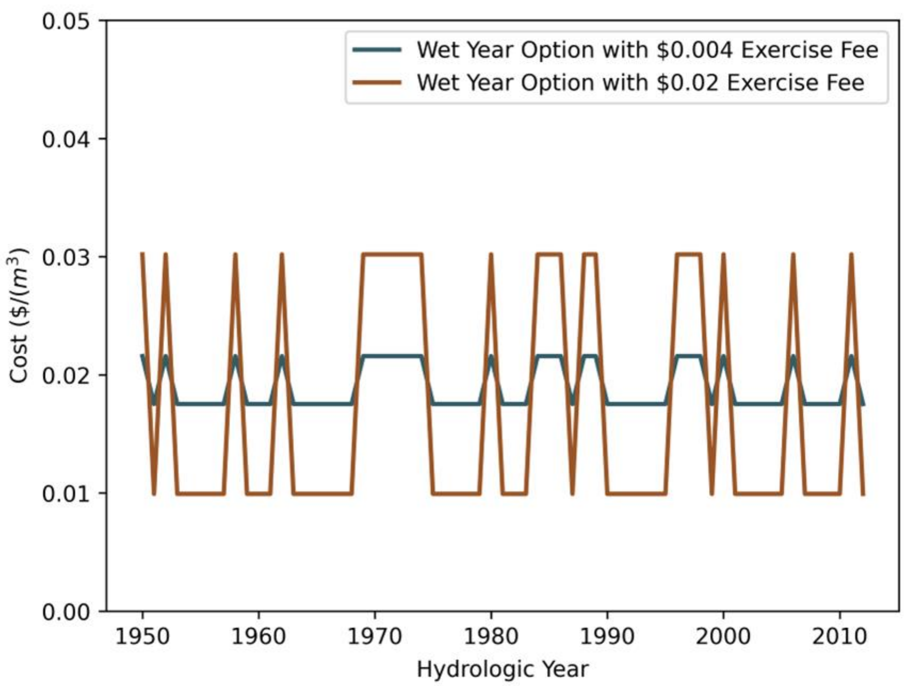

Figure S2. *Wet year pricing of the two-way option with varying exercise fees in the current rights regime under pricing scenario 1.*

Text S3.

While data detailing municipal leasing to irrigators in wet years is sparse, the City of Boulder has recorded the amount of water it leases in its municipal bond offerings. Figure 1 shows the amount of water right holdings from Northern Water Municipalities compared to their demands. The difference between these right holdings and demands is what we define as surplus water rights holdings. Using the City of Boulder's records on water leased back to irrigators and Boulder's water rights surplus in years that it leases back, we identify the amount of their surplus they choose to lease. In this analysis, we assume the percentage of leasable surplus is consistent across all Northern Water municipalities, that is, that the other communities are comfortable leasing a similar fraction. Since these values are associated with information on hydrologic conditions in that year as measured by the CBI, a relationship between potential leases and hydrologic conditions is used to determine a lease volume in wet years when CBI > 800 (Equation A5), consistent with Section 3.2.

$$Lease_y = 0.036 \cdot CBI_y - 8.42 \tag{A5}$$

Where, $Lease_y$ = amount of lease available to irrigators (MCM), CBI_y = CBI Index Value

In the scenarios in which two-way options are available in the past, i.e. when municipal water rights holdings were similar to that held in 1971, the amount of 'surplus' water rights holdings will change proportional to the lower volume of water rights held by Northern Water municipalities in 1971. Using the same leasable percentages for a given CBI value, a new relationship describes the available surplus (Equation A6).

$$Lease_y = 0.015 \cdot CBI_y - 3.50 \tag{A6}$$

These relationships are used in conjunction with the CBI triggers to project the amount of leasable water to irrigators which are used to understand two-way option pricing.

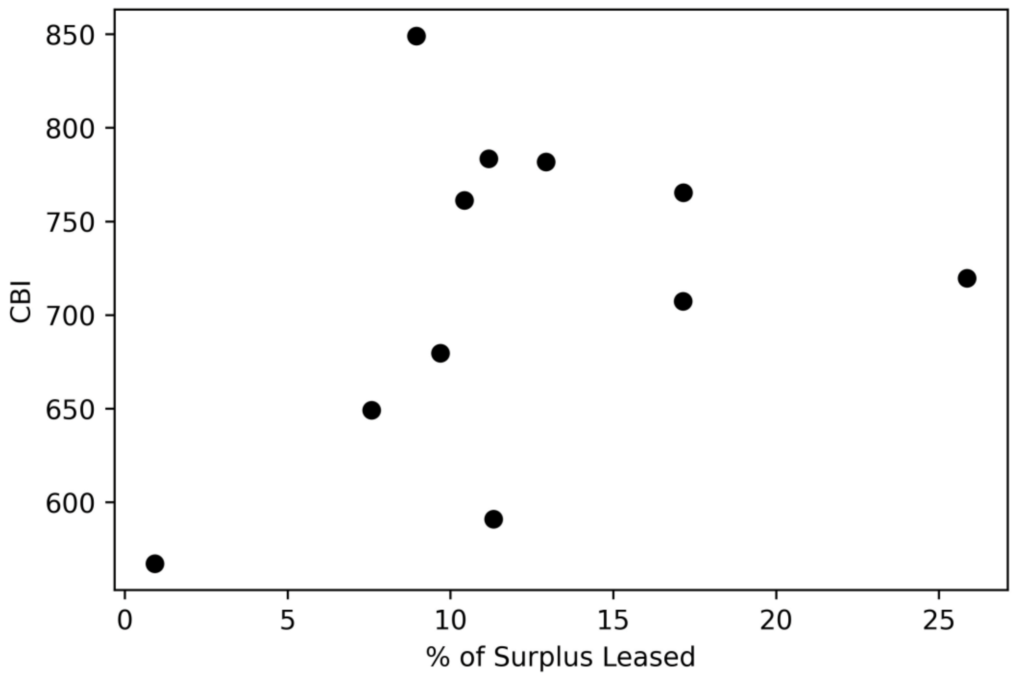

Figure S3. *Percentage of surplus leased from the City of Boulder with the corresponding CBI value*

Table S3. *Pricing Scenarios used in the Current Rights regime with distribution of simulated lease prices*

	Current Water Rights Holdings	
	Ag-to-Urban lease price (Dry years)	**Urban-to-Ag lease price (Wet years)**
Scenario 1	$0.001 - $0.023/m^3* ($1.41 - $28.12/AF)	$0.031 - $0.037/m^3** ($37.69 - $46.25/AF)
Scenario 2	$0.001 - $0.023/m^3* ($1.41 - $28.12/AF)	$0.02/m^3 ($30/AF)
Scenario 3	$0.81/m^3 ($1000/AF)	$0.02/m^3 ($30/AF)
Scenario 4	$0.81/m^3 ($1000/AF)	$0.031 - $0.037/m^3** ($37.69 - $46.25/AF)

*Market-clearing price range over dry years; **Market-clearing price range over wet years

Table S4. *Pricing Scenarios used in the 1971 Rights regime with distribution of simulated lease prices*

	1971 Water Rights Holdings	
	Ag-to-Urban lease price	**Urban-to-Ag lease price**
Scenario 1	$0.023- $0.026/m^3* ($28.12 - $32.48/AF)	$0.05 - $0.09/m^3** ($58.93 - $108.35/AF)
Scenario 2	$0.023- $0.026/m^3* ($28.12 - $32.48/AF)	$0.02/m^3 ($30/AF)
Scenario 3	$0.81/m^3 ($1000/AF)	$0.02/m^3 ($30/AF)
Scenario 4	$0.81/m^3 ($1000/AF)	$0.05 - $0.09/m^3** ($58.93 - $108.35/AF)

*Market-clearing price range over dry years; **Market-clearing price range over wet years

Table S5. *Two-way option performance with current water rights holdings under pricing scenarios 2 & 4*

Current Rights Holdings	Scenario 2 Lease Prices: Ag-Urban: \$0.001 - \$0.023/m^3 (\$1.41 - \$28.12/AF) Urban-Ag: \$0.02/m^3 (\$30/AF)	Scenario 4 Lease Prices: Ag-Urban: \$0.81/m^3 (\$1000/AF) Urban-Ag: \$0.031 - \$0.037/m^3 (\$37.69 - \$46.25/AF)
Agricultural Gains (\$M)	9.5	25.2
Two-way option cost to Ag*^ (\$/m^3) \$/AF)	0.04 (47.6)	0.04 (52.6)
Two-way option cost to Urban** ^ (\$/m^3) (\$/AF)	0.03 (34.4)	0.94 (1160.1)
Total two-way option cost to Urban (\$M)	0.5	17.4
Urban savings from two-way option usage (\$M)	325	308.6

*Assumes exercise fee of \$0.01/m^3 (\$15/AF) in Scenario 2, Assumes \$0.02/m^3 (\$25/AF) exercise fee in Scenario 4; ** Assumes exercise fee of \$0.02/m^3 (\$25/AF) in Scenario 2, Assumes \$0.57/m^3 (\$700/AF) exercise fee in Scenario 4; ^ Average option cost calculated using the sum of all option fees and exercise fees across the simulation, divided by the total amount of water re-allocated.

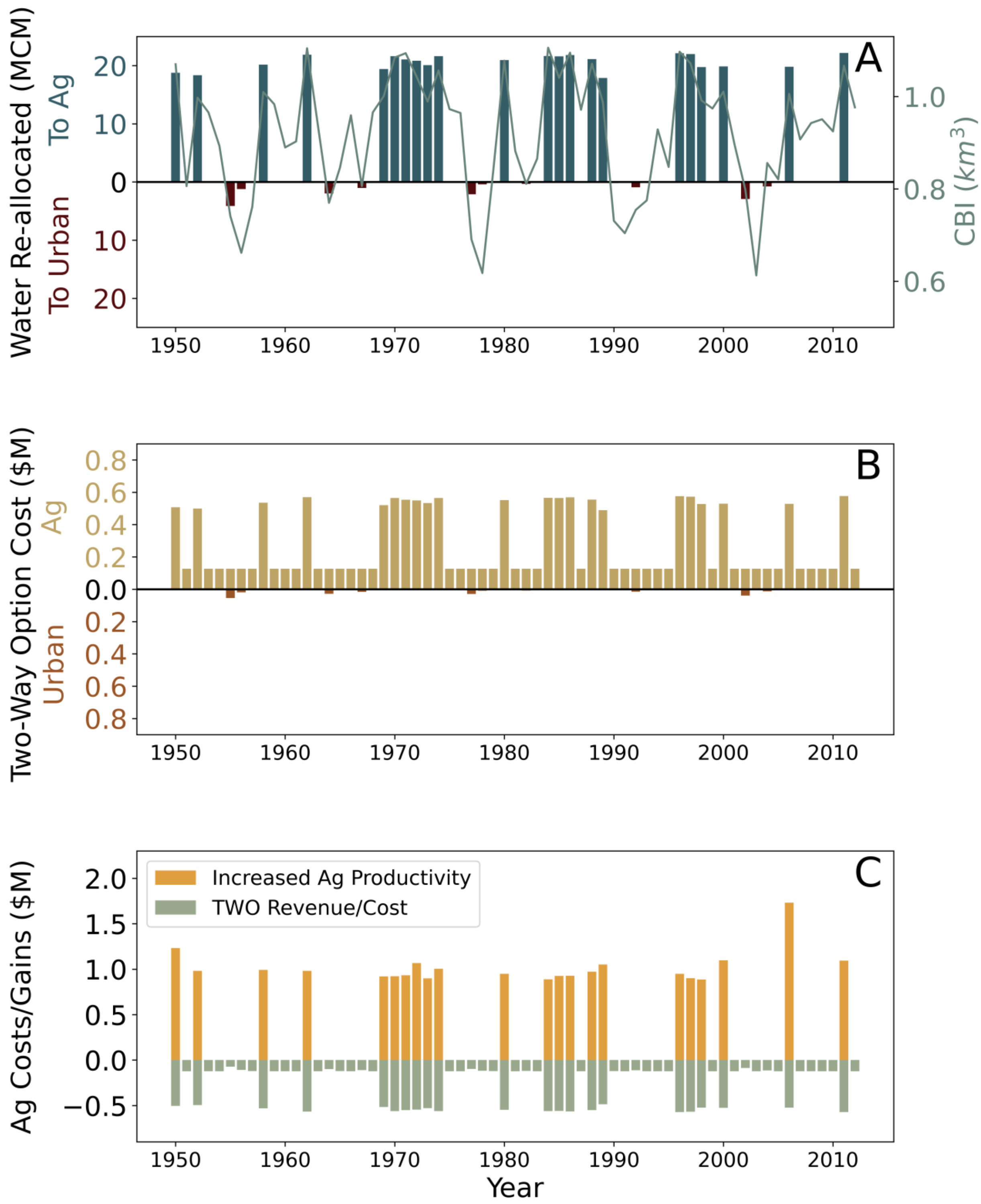

Figure S4. *Two-way option performance with current water rights under pricing scenario 2*

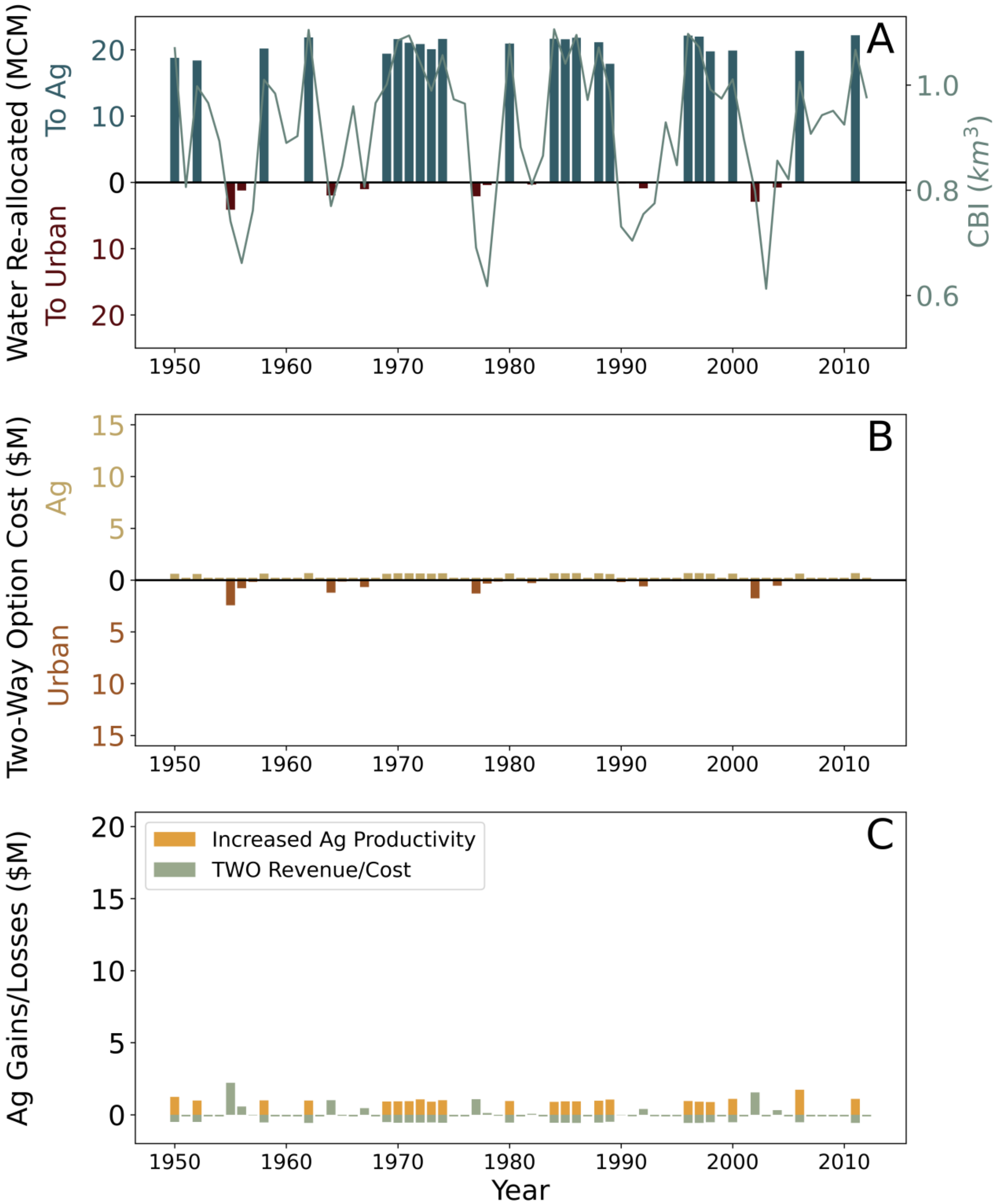

Figure S5. *Two-way option performance with current water rights under pricing scenario 4*

Table S6. *Two-way option performance with 1971 water rights holdings under pricing scenarios 2 & 4*

1971 Rights Holdings	Scenario 2 Lease Prices: Ag-Urban: \$0.001 - \$0.023/m^3 (\$1.41 - \$28.12/AF) Urban-Ag: \$0.02/m^3 (\$30/AF)	Scenario 4 Lease Prices: Ag-Urban: \$0.81/m^3 (\$1000/AF) Urban-Ag: \$0.031 - \$0.037/m^3 (\$37.69 - \$46.25/AF)
Agricultural Gains (\$M)	15.78	181.62
Two-way option cost to Ag*^ (\$/m^3) (\$/AF)	0.03 (35.87)	0.09 (108.14)
Two-way option cost to Urban** ^ (\$/m^3) (\$/AF)	0.03 (38.16)	0.92 (1132.91)
Total two-way option cost to Urban (\$M)	6.03	179
Urban savings from two-way option usage^^ (\$M)	290	117

*Assumes exercise fee of \$0.01/m^3 (\$15/AF) in Scenario 2, Assumes \$0.02/m^3 (\$25/AF) exercise fee in Scenario 4; ** Assumes exercise fee of \$0.02/m^3 (\$25/AF) in Scenario 2, Assumes \$0.57/m^3 (\$700/AF) exercise fee in Scenario 4; ^ Average option cost calculated using the sum of all option fees and exercise fees across the simulation, divided by the total amount of water re-allocated ; ^^Assumes water right purchases in 1971 were at \$1.62/m^3 (\$2000/AF), adjusted to 2023 dollars

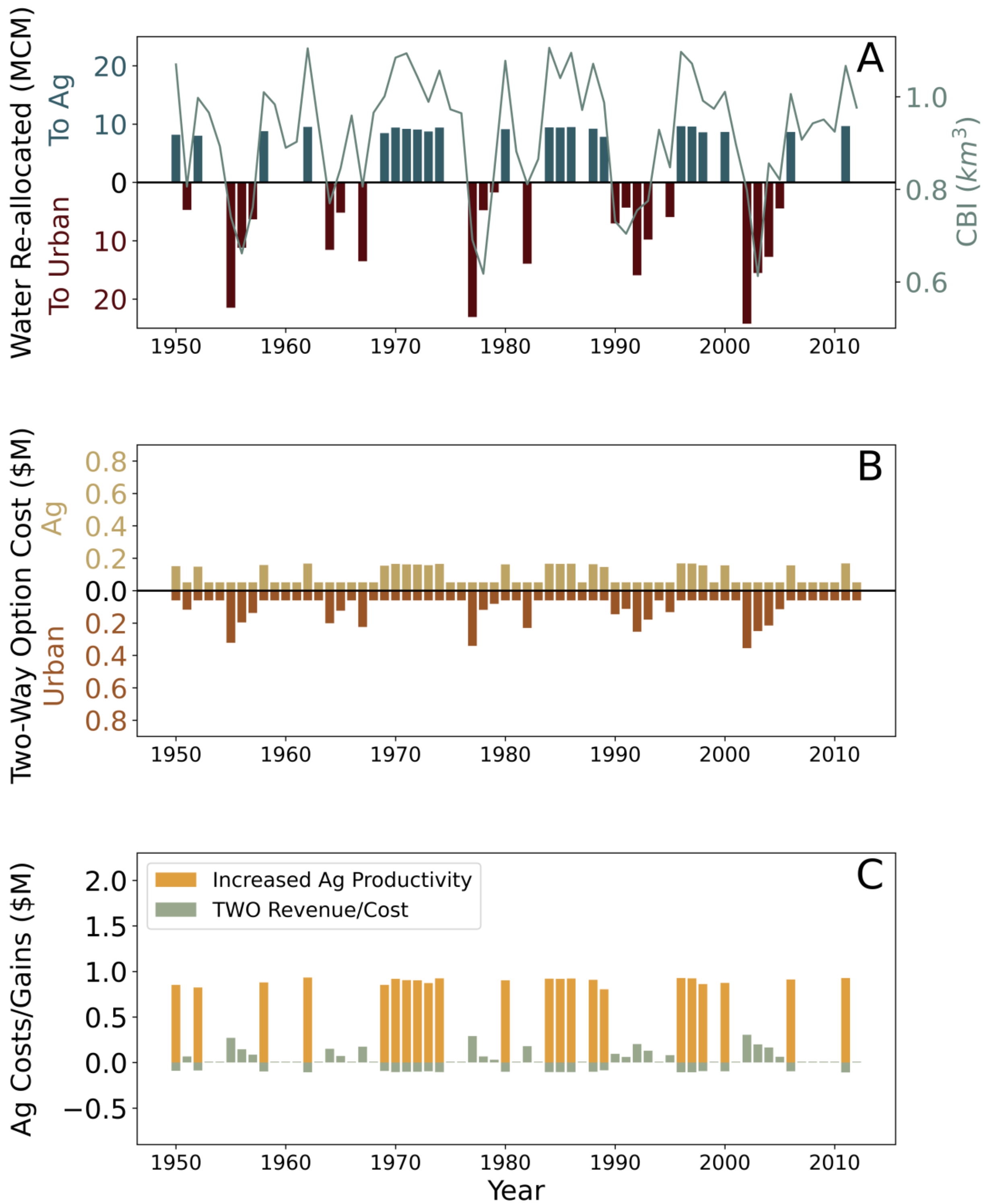

Figure S6. *Two-way option performance with 1971 water rights under pricing scenario 2*

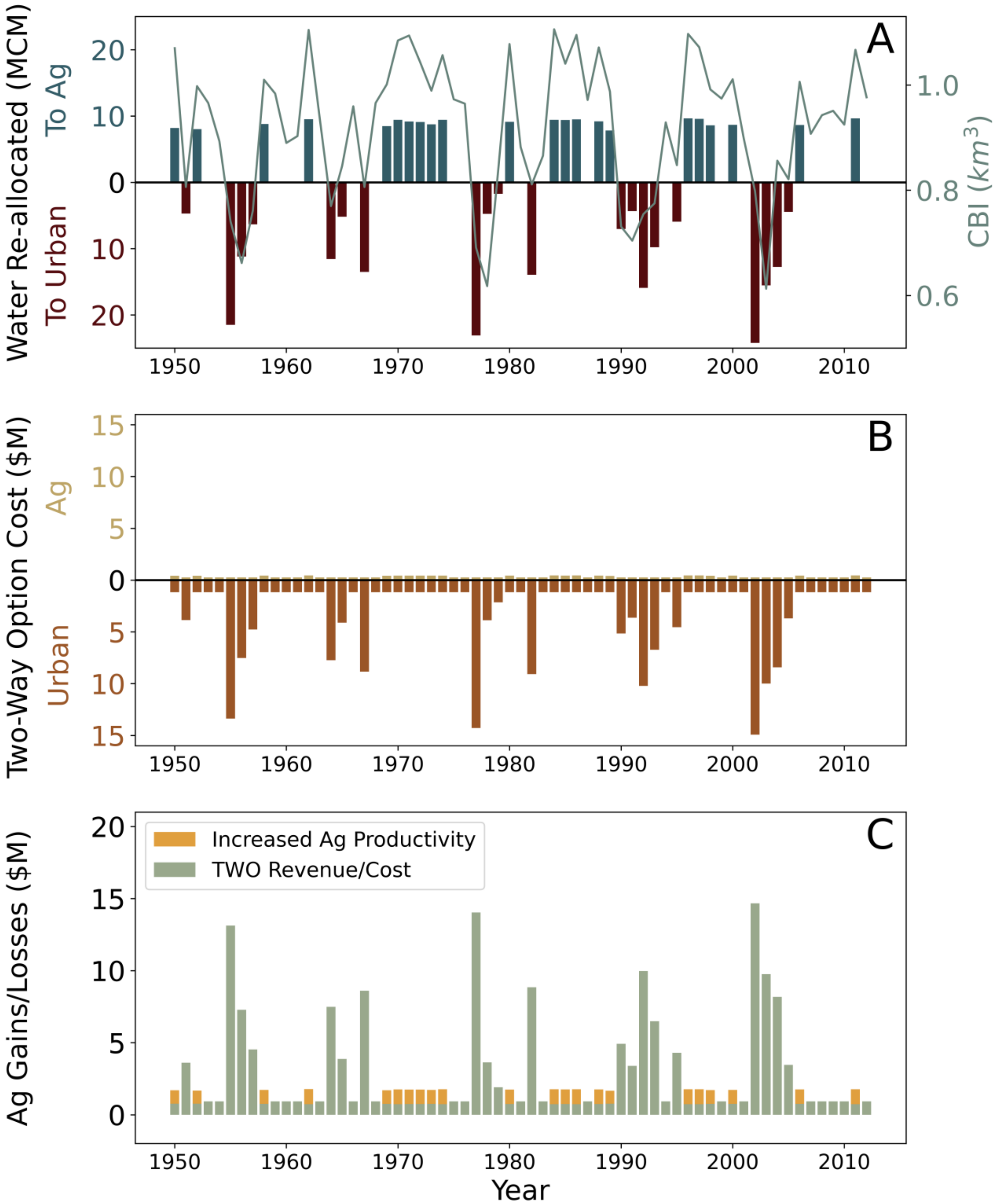

Figure S7. *Two-way option performance with 1971 water rights under pricing scenario 4*