Dual rights to groundwater: Theory and application to California[1]

Louis Sears and C.-Y. Cynthia Lin Lawell

Abstract

Groundwater property rights in California are governed by a dual rights system, in which the primary right to groundwater is given to the owner of land "overlying" the resource, while appropriators may divert water that is unused by the overlying user to beneficial uses outside of the land. We develop a theory of such a dual rights system, and compare it to a single rights system and to the social optimum. We then apply our model to California to numerically analyze the inefficiencies that arise from the dual rights system in California. Our results show that a dual rights system can be inefficient and lead to deadweight loss. In particular, owing to inefficiencies from allocating property rights based on historical use, the common pool nature of the groundwater resource, and differences in the marginal value of water between the farmer and the appropriator, a dual rights system can lead to groundwater overextraction.

Keywords: groundwater, property rights, dual rights
***JEL* codes:** Q38, Q15, P14
This draft: September 2018

[1] Sears: Cornell University; lss34@cornell.edu. Lin Lawell: Cornell University; clinlawell@cornell.edu. David Lim provided excellent research assistance. We thank Yuan Chen, Ariel Dinar, Ken Gillingham, Christina Korting, Gabe Lade, Martino Pelli, Irvin Rojas, Ivan Rudik, Brian Shin, Arthur van Benthem, Steven Wilcox, and David Zilberman for detailed and helpful comments. We also benefited from comments from seminar participants at Cornell University; and conference participants at the Canadian Resource and Environmental Economics Study Group Annual Conference, the Conference celebrating the 25th Anniversary of Douglass North's Nobel Prize in Economics at George Mason University, and the Tenth Annual Meeting of the Society for Environmental Law and Economics. We received funding from a Cornell University Institute for the Social Sciences Small Grant; the Giannini Foundation of Agricultural Economics; and the 2015-2016 Bacon Public Lectureship and White Paper Competition. All errors are our own.

1. Introduction

Many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels (Sears and Lin Lawell, 2019). In California, which produces almost 70 percent of the top 25 fruit, nut, and vegetable crops in the United States (Howitt and Lund, 2014), current levels of groundwater use are unsustainable (Famiglietti, 2014).

Groundwater users extract water under an institutional setting that governs their property rights to the groundwater and affects the constraints they face and the choices they make (Lin Lawell, 2018). Groundwater property rights in California are governed by a dual rights system, in which the primary right to groundwater is given to the owner of land "overlying" the resource, while appropriators may divert water that is unused by the overlying user to beneficial uses outside of the land (SWRCB, 2017; Bartkiewicz et al., 2006).

In a dual rights system, the overlying property right owner, who in most cases in California is a farmer using groundwater for agricultural irrigation; and the appropriator, which in most cases in California is a water district, are both extracting from the groundwater resource. When the farmer and the appropriator behave non-cooperatively, such a dual rights system may lead to inefficiencies relative to a single rights system in which the overlying property right owner has the exclusive right to extract from the resource, and also relative to the social optimum.

In this paper, we develop a theory of a dual rights system, and compare it to a single rights system and to the social optimum. We then apply our model to California to numerically analyze the inefficiencies that arise from the dual rights system in California.

Our results show that a dual rights system can be inefficient and lead to deadweight loss. In particular, owing to inefficiencies from allocating property rights based on historical use, the common pool nature of the groundwater resource, and differences in the marginal value of water between the farmer and the appropriator, a dual rights system can lead to groundwater overextraction.

The balance of this paper proceeds as follows. We provide background information on property rights for groundwater in Section 2. We present our theoretical model of a dual property rights system in Section 3. We describe our application to California in Section 4. We present our results in Section 5. Section 6 concludes.

2. Property rights to groundwater

The design of property rights systems to groundwater affects groundwater extraction decisions and their efficiency. A variety of property rights doctrines and institutions governing groundwater have evolved in the western United States. Many more institutions, both formal and informal, are in place in other locations around the world (Lin Lawell, 2018). In this section, we describe the dual rights system in California and discuss the design of property rights to groundwater.

2.1. California's dual rights system

Groundwater property rights in California are governed by a dual rights system, which is a system with two forms of groundwater property rights. First, the primary right to groundwater is given to the owner of land "overlying" the resource; these overlying property rights allow owners of the land to beneficially use a reasonable share of any groundwater basin lying below the surface of the land. In most cases in California, the overlying property right owner is a farmer using groundwater for agricultural irrigation. Second, any surplus groundwater from the basin may then be beneficially used or sold by individuals or businesses who do not own land directly overlying the basin through an appropriative right; these appropriators may divert water that is unused by the overlying user to beneficial uses outside of the land. In most cases in California, the appropriator is a water district that combines rights to surface water with appropriated groundwater for use throughout the boundaries of their administrative zones (SWRCB, 2017; Bartkiewicz et al., 2006).[2]

The dual rights system in California is designed to operate under both instances of surplus groundwater, when inflow exceeds the use of overlying users; and overdraft, when the groundwater table begins to decline due to extraction exceeding inflows. Appropriative groundwater rights are subordinate to overlying rights, and in times of overdraft a "first in line" system requires that more recent appropriative users cease their extraction (Sears, Lim and Lin Lawell, 2018).

[2] California's system of dual rights arose from a 1903 California Supreme Court decision in the case of Katz v. Walkinshaw, which put an end to a period of "absolute ownership" rights, which guaranteed landowners the right to unlimited use of water underneath their properties (California State Water Resources Control Board, 2011; Sears, Lim and Lin Lawell, 2018).

In practice, though, the dual rights system relies on California's court system adjudicating property rights during periods of overdraft. The court's response to these periods has varied widely over time. Prior to 1949, appropriative right holders could obtain a "prescriptive right" that was senior to overlying rights by demonstrating that they had extracted from an overdrafted basin for at least five consecutive years (Lambert, 1984; Sears, Lim and Lin Lawell, 2018).

The California State Supreme Court moderated this position in 1949 by creating a system of "mutual prescription" in which users of an overdrafted basin were allocated extraction in proportion to their prior use, and total extraction was to be within a "safe yield" (California DWR, 2003). This created an incentive for overdrafted basin users to expand their groundwater use during times of overdraft, in order to receive a more favorable court allocation. Mutual prescription was modified in 1975 so that it could not infringe on public water agencies' rights to groundwater (California DWR, 2003). In addition, the state legislature later moderated this by allowing the adjudicated allocation to be based also on supplemental water used in lieu of groundwater during an overdraft period (Lambert, 1984; California Water Code 1005.1-4; Sears, Lim and Lin Lawell, 2018).[3]

2.2. Design considerations for property rights to groundwater

There are many important issues to consider when designing property rights to groundwater. When assigning water rights rights to landowners, policy-makers in California were initially more concerned with encouraging the settlement and productive use of arable land than with allocative or dynamic economic efficiency; and they only began to consider efficiency of how water was allocated after the surplus of unused land had disappeared (Zilberman et al., 2017).

One important feature of groundwater that must be accounted for in the design of groundwater property rights is the common pool nature of the groundwater resource: because groundwater users are sharing the aquifer with other groundwater users, other groundwater users' pumping affects their extraction cost and the amount of water they have available to pump. Consequently, groundwater pumping by one user raises the extraction cost and lowers the total amount that is available to other nearby users (Pfeiffer and Lin, 2012; Lin Lawell, 2016; Sears and Lin Lawell, 2019). Property rights to common pool resources can be differentiated into

[3] A more detailed description, discussion, and analysis of the adjudication process is provided in Sears and Lin Lawell (2018).

operational and collective choice rights (Schlager and Ostrom, 1992). Operational rights include the right to access and withdraw from the common pool. Collective action rights give users the rights to management (the right to regulate of the resource), exclusion (the right to determine who will have access), and alienation (the right to sell or lease the resource).

Another important feature of groundwater that must be accounted for in the design of groundwater property rights is that groundwater resources are at least partially nonrenewable, and must therefore be managed dynamically (Lin Lawell, 2018; Sears and Lin Lawell, 2019). Schlager and Ostrom (1992) argue that the rights to alienation and exclusion are necessary for undertaking long-term investment in the resource, since they guarantee that the owner will capture the benefits from investment. Property rights systems such as the prior appropriation doctrine that do not account for the nonrenewable nature of groundwater may distort the incentive for rights-holders to optimize dynamically, leading to a deviation from the economically efficient extraction path (Lin Lawell, 2018).

Groundwater rights in California within a single basin represent a situation in which there are different property rights to a common pool resource. Each groundwater sustainability agency (GSA) has both exclusion and management power within its administrative zone, through its ability to set sustainable yield and regulate the use of other participants. The water district that is not part of a GSA may lack some of the powers of regulation and exclusion, but due to their scale and the lowering of transaction costs, they have some right to alienation through water transfers. Transaction costs make the rights to exclusion, through adjudication and alienation through water transfer difficult for the individual farmer.

A second dimension along which rights can property rights can be classified is between de jure and de-facto rights (Schlager and Ostrom, 1992). De jure rights are given by the government, and can be expected to be upheld in court when they are challenged (Schlager and Ostrom, 1992). De-facto rights originate within the users, and can only be enforced by the users, not by the court (Schlager and Ostrom, 1992).

Groundwater rights in California, and the inconsistency of their enforcement, bear traits of both types of rights. Groundwater rights are state granted rights, and they can be challenged and defined more formally through the process of adjudication (Langridge et al., 2017). However, the process is lengthy, expensive, and perhaps most importantly, due to the inconsistency of rulings throughout history, the criteria that Schlager and Ostrom (1992) use to define de jure rights, that "right-holders who have de jure rights can presume that if their rights were challenged in an administrative or judicial setting, their rights would most likely be sustained" does not hold (Langridge et al., 2017; Schlager and Ostrom, 1992). Thus, groundwater rights in California have historically lacked the formality of de jure rights.

The security of property rights to a common pool resource is predicted to have a positive impact on productive use of the resource. In the absence of formal property rights, the effort devoted to extracting the resource rises with the number of competitors in the economy, the importance of the resource in production, and the degree of insecurity of the property right (Grossman, 2001). In his analysis of the value created by clarifying property rights for water in Idaho, Browne (2018) finds that water rights trading moved water to relatively more productive use, and that the Snake River Basin Adjudication increased total crop acreage by 4% and increased the value of Idaho's agricultural output by $250 million per year. Tsvetanov and Earnhart (2018) employ a difference-in-differences framework to assess the effectiveness of the Kansas Water Right Transition Assistance Program (WTAP), which compensates water users for the voluntary retirement of their water rights, and find that water right retirement in High Priority Areas substantially reduced groundwater extraction.

Ayres et al. (2018) identify two sources of value created by adjudicating groundwater rights in Southern California that are capitalized into land values. First, owners of land within an adjudicated region receive value directly from ownership of water rights. Second, there is value gained through improving the management of the aquifer that also spills over to owners of land overlying the same aquifer but outside of the management zone. Using data from the Mojave basin adjudication, Ayres et al. (2018) find that there are larger gains from landowners inside management zones than outside.

In order for the use of a common pool resource to be socially optimal, it is important not only to have secure property rights, but also to identify, and keep track of, and assert property rights (Sweeney, Tollison, and Willet, 1974). In the examples of fisheries and oil, Sweeney, Tollison, and Willet (1974) argue that common pool resource management arises from the fact that individual property rights may be difficult to identify, keep track of, and are not economical to enforce. This makes the right only profitable to exercise through extraction, which is equivalent to open access, where the only property right is extraction in the current period. Thus, even in the case of formal property rights, transaction costs related to the creation and monitoring of property rights may lead to open access management instead of dynamic efficiency. Furthermore, in the absence of metering, Wallander (2017) notes that farmers may over-irrigate due to an incomplete understanding of how much water has been applied.

Granting multiple users a property right to a common pool resource may lead to inefficiency. Our result that dual rights to groundwater can be inefficient corroborates the insight of Fitzgerald (2010), who finds that oil and gas leases that are "split estate" in which the appropriator does not have surface rights in addition to mineral rights, are discounted relative to exclusive leases, and that this lease discount is more pronounced in expensive leases (Fitzgerald, 2010).

3. Theory

In a dual rights system, the overlying property right owner, who is in most cases in California is a farmer using groundwater for agricultural irrigation; and the appropriator, which is most cases in California is a water district, are both be extracting from the groundwater resource. We develop a theory of such a dual rights system, and compare it to a single rights system and to the social optimum.

3.1. Single rights system

We begin with a single rights regime, in which water is used exclusively for farming. Under a single rights system, the farmer *f* owns the exclusive right to extract water from the overlying land. In this model, the farmer *f* determines optimal trajectory for water extraction $w_f(t)$ and investment $I_f(t)$ in capital $K_f(t)$ for each time *t*. Since the groundwater that is extracted is used to irrigate crops, we also refer to water extraction $w_f(t)$ as "applied water". Capital $K_i(t)$ represents both wells drilled as well as technology that improves the efficiency of extraction and irrigation, and therefore both increases the marginal revenue from extraction and decreases the cost of extraction.

Let $R_f(w_f(t), K_f(t))$ denote the per-period revenue to the farmer that can be generated by producing crops with extracted irrigation water $w_f(t)$ and capital $K_f(t)$, assuming crops are chosen optimally to maximize revenue given extracted irrigation water $w_f(t)$. Capital $K_f(t)$ increases both revenue and the marginal revenue of extraction: $\frac{\partial R_f(w_f(t), K_f(t))}{\partial K} > 0$ and $\frac{\partial^2 R_f(w_f(t), K_f(t))}{\partial w \partial K} > 0$, respectively.

Let $C^w(w_f(t), s(t), K_f(t))$ denote the cost of extracting water $w_f(t)$, which depends on the distance that the water must be pumped from the aquifer to the surface of the ground, as well as on capital $K_f(t)$. The distance the water must be pumped depends on the stock of water $s(t)$; as the stock decreases, pumping cost increases, or $\frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial s} < 0$. Further, assume that as the resource becomes very scarce, extraction costs become infinite, or $\lim_{s \to 0} \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial s} = -\infty$. Capital $K_f(t)$ decreases costs: $\frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial K} < 0$.

Let's assume there is a quadratic adjustment cost to investment, so that the cost of investment is given by:

$$C^I(I_f(t)) = I_f(t) + \alpha_f I_f^2(t). \tag{1}$$

The per-period profits to the farmer owning both the rights to appropriate groundwater and the rights to the overlying land can thus be written as:

$$\pi_f(t) = R_f(w_f(t), K_f(t)) - C^w(w_f(t), s(t), K_f(t)) - C^I(I_f(t)). \tag{2}$$

We assume that the state variable evolves according to a simple deterministic equation:

$$\dot{s}(t) = -w_f(t) + \gamma(t), \tag{3}$$

where $\gamma(t)$ is the known path of natural recharge and $\lambda_s(t)$ is the associated multiplier. The capital stock K_{ft} evolves according to the deterministic equation:

$$\dot{K}_f(t) = -\delta K_f(t) + I_f(t), \tag{4}$$

where δ is a constant depreciation rate and $\lambda_K(t)$ is the associated multiplier.

Farmer *i*'s optimal control problem is therefore given by:

$$\max_{\{w_f(t),I_f(t)\}} \int_0^{\infty} \Big(R_f(w_f(t),K_f(t)) - C^w(w_f(t),s(t),K_f(t)) - C^I(I_f(t)) \Big) e^{-rt} \tag{5}$$

subject to:

$$\dot{s}(t) = -w_f(t) + \gamma(t) \,,$$

$$\dot{K}_f(t) = -\delta K_f(t) + I_f(t) \,,$$

where r is the discount rate.

The farmer's Hamiltonian function can then be written as:

$$\begin{aligned} H_f(t) = R_f(w_f(t),K_f(t)) - C^w(w_f(t),s(t),K_f(t)) - C^I(I_f(t)) \\ + \lambda_s(t)(-w_f(t)+\gamma(t)) + \lambda_K(t)(-\delta K_f(t) + I_f(t)) \end{aligned} , \tag{6}$$

where the Pontryagin first-order conditions are given by:

$$\begin{aligned}
&[\#1s]: && \frac{\partial R_{ft}(w_f(t),K_f(t))}{\partial w} = \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial w} + \lambda_s(t) \\
&[\#1K]: && \frac{dC^I(I_f(t))}{dI} = \lambda_K(t) \\
&[\#2s]: && \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial s} = \dot{\lambda}_s(t) - r\lambda_s(t) \\
&[\#2K]: && -\frac{\partial R_{ft}(w_f(t),K_f(t))}{\partial K} + \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial K} + \delta\lambda_K(t) = \dot{\lambda}_K(t) - r\lambda_K(t)
\end{aligned} ,$$

where the multipliers $\lambda_s(t)$ and $\lambda_K(t)$ on resource stock and capital stock, respectively, are both non-negative.

The farmer's marginal net benefit $MNB_f(\cdot)$ from water extraction is given by:

$$MNB_f(w_f(t),s(t),K_f(t)) = \frac{\partial R_f(w_f(t),K_f(t))}{\partial w} - \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial w} \,. \tag{7}$$

3.2. Dual rights system

Now we add a second agent to the model, the appropriator. The two agents share a common stock $s(t)$ of groundwater, meaning that the depth to groundwater is the same for each. The stock of groundwater now evolves according to the following deterministic equation:

$$\dot{s}(t) = -w_f(t) - w_a(t) + \gamma(t)\,, \tag{8}$$

where $w_a(t)$ is water extraction by the appropriator, $\gamma(t)$ is the known path of natural recharge, and $\lambda_s(t)$ is the associated multiplier.

The appropriator sells water $w_a(t)$ at price $p_w(t)$ rather than using it, and earns per period revenues $R_a(w_a(t))$ given by:

$$R_a(w_a(t)) = p_w(t) w_a(t)\,. \tag{9}$$

The appropriator invests in capital $K_a(t)$ to improve the efficiency of extraction. The period profit function for the appropriator can then be written as:

$$\pi_a(t) = R_a(w_a(t)) - C^w(w_a(t), s(t), K_a(t),) - C^I(I_a(t))\,. \tag{10}$$

The appropriator's marginal net benefit $MNB_a(\cdot)$ from water extraction is given by:

$$MNB_a(w_a(t), s(t), K_a(t)) = \frac{\partial R_a(w_a(t))}{\partial w} - \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial w}\,. \tag{11}$$

We examine two different versions of a dual rights system. The first dual rights system we examine is dual rights under open access, in which each player is free to extract at any level. The second dual rights system we examine is dual rights where the appropriator's property rights to water are based on historical use. We compare open access and historical use, and examine cases in which historical use may be more inefficient than open access.

3.2.1. Open access dual rights system

The first dual rights system we examine is dual rights under open access, in which each player is free to extract at any level. Under open access dual rights, the Hamiltonian of the farmer is given by equation (6), and the Hamiltonian for the appropriator is given by:

$$\begin{aligned} H_a(t) = R_a(w_a(t)) - C^w(w_a(t), s_t, K_a(t)) - I_a(t) - C^I(I_a(t)) \\ +\lambda_{sa}(t)(-w_a(t) - w_f(t) + \gamma(t))\,. \\ +\lambda_{Ka}(t)(-\delta K_a(t) + I_a(t)) \end{aligned} \tag{12}$$

The Pontryagin first-order conditions are then given by:

$$[\#1sf]: \quad \frac{\partial R_f(w_f(t),K_f(t))}{\partial w} = \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial w} + \lambda_{sf}(t)$$

$$[\#1Kf]: \quad \frac{dC^I(I_f(t))}{dI} = \lambda_{Kf}(t)$$

$$[\#2s]: \quad \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial s} = \dot{\lambda}_s(t) - r\lambda_s(t)$$

$$[\#2Kf]: \quad -\frac{\partial R_f(w_f(t),K_f(t))}{\partial K} + \frac{\partial C^w(w_f(t),s(t),K_f(t))}{\partial K} + \delta\lambda_{Kf}(t) = \dot{\lambda}_{Kf}(t) - r\lambda_{Kf}(t)$$

$$[\#1sa]: \quad \frac{\partial R_a(w_a(t))}{\partial w} - \frac{\partial C^w(w_a(t),s(t),K_a(t))}{\partial w} = \lambda_{sa}(t)$$

$$[\#1Ka]: \quad \frac{dC^I(I_a(t))}{dI} = \lambda_{Ka}(t)$$

$$[\#2sa]: \quad \frac{\partial C^w(w_a(t),s(t),K_a(t))}{\partial s} = \dot{\lambda}_{sa}(t) - r\lambda_{sa}(t)$$

$$[\#2Ka]: \quad \frac{\partial C^w(w_a(t),s(t),K_f(t))}{\partial K} + \delta\lambda_{Ka}(t) = \dot{\lambda}_{Ka}(t) - r\lambda_{Ka}(t) \,. \tag{13}$$

3.2.2. Historical use dual rights system

The second dual rights system we examine is dual rights where the appropriator's property rights to water are based on historical use. In particular, the cap on appropriator groundwater extraction is based on historical use $W_a(t)$ of the resource as well as a share σ of the groundwater stock $s(t)$ as follows:

$$w_a(t) \le W_a(t) + \sigma s(t), \tag{14}$$

where the historical use $W_a(t)$ evolves as a τ-period moving average of the appropriator's prior pumping:

$$\dot{W}_a(t) = \frac{w_a(t) - W_a(t)}{\tau}. \tag{15}$$

Under historical use dual rights, the Hamiltonian of the farmer is again given by equation (6), and the Hamiltonian for the appropriator is given by:

$$
\begin{aligned}
H_a(t) = R_a(w_a(t)) - C^w(w_a(t), s_t, K_a(t)) - I_a(t) - C^I(I_a(t)) \\
+\lambda_{sa}(t)(-w_a(t) - w_f(t) + \gamma(t)) \\
+\lambda_{Ka}(t)(-\delta K_a(t) + I_a(t)) . \\
+\lambda_{Wa}\frac{w_a(t) - W_a(t)}{\tau} \\
+\lambda_{wa}(W_a(t) + \sigma s(t) - w_a(t)
\end{aligned}
\tag{16}
$$

where λ_{Wa} is the non-negative multiplier on the equation of motion for historical use $W_a(t)$, and and λ_{wa} is the non-negative multiplier on the constraint on appropriator water extraction $w_a(t)$.

The Pontryagin first-order conditions are then given by:

$$
\begin{aligned}
&[\#1sf]: && \frac{\partial R_f(w_f(t), K_f(t))}{\partial w} = \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial w} + \lambda_{sf}(t) \\
&[\#1Kf]: && \frac{dC^I(I_f(t))}{dI} = \lambda_{Kf}(t) \\
&[\#2s]: && \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial s} = \dot{\lambda}_s(t) - r\lambda_s(t) \\
&[\#2Kf]: && -\frac{\partial R_f(w_f(t), K_f(t))}{\partial K} + \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial K} + \delta\lambda_{Kf}(t) = \dot{\lambda}_{Kf}(t) - r\lambda_{Kf}(t) \\
&[\#1sa]: && \frac{\partial R_a(w_a(t))}{\partial w} - \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial w} + \frac{\lambda_{Wa}}{\tau} - \lambda_{wa} = \lambda_{sa}(t) \\
&[\#1Ka]: && \frac{dC^I(I_a(t))}{dI} = \lambda_{Ka}(t) \\
&[\#2sa]: && \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial s} - \sigma\lambda_{wa} = \dot{\lambda}_{sa}(t) - r\lambda_{sa}(t) \\
&[\#2Ka]: && \frac{\partial C^w(w_a(t), s(t), K_f(t))}{\partial K} + \delta\lambda_{Ka}(t) = \dot{\lambda}_{Ka}(t) - r\lambda_{Ka}(t) \\
&[\#2Wa]: && \frac{\lambda_{Wa}}{\tau} - \lambda_{wa} = \dot{\lambda}_{Wa}(t) - r\lambda_{Wa}(t) . \\
&[CS]: && \lambda_{wa}\left(W_a(t) + \sigma s(t) - w_a(t)\right) = 0
\end{aligned}
\tag{17}
$$

3.3. Social Optimum

We finally model the decision making of a social planner who has the ability to extract water for both farming and appropriation. In this model, the social planner determines the optimal path of investment in productive capital and extraction for both uses from a single stock of groundwater s. The social planner then optimizes a single profit function with the following form:

$$\pi_s(t) = R_s(w_f(t), w_a(t), K_f(t)) - C_s^w(w_f(t), w_a(t), s(t), K_f(t), K_a(t)) - C^I(I_f(t)) - C^I(I_a(t)). \quad (18)$$

The social planner's revenue function includes revenues from both farming and appropriation and can be written as:

$$R_s(w_f(t), w_a(t), K_f(t)) = R_f(w_f(t), K_f(t)) + R_a(w_a(t)), \quad (19)$$

where functional forms for both component revenue functions are taken to be the same as in the dual rights case. Similarly, the cost function for extraction can be written using the cost functions of the dual rights case as its components:

$$C_s^w(w_f(t), w_a(t), s(t), K_f(t), K_a(t)) = C^w(w_f(t), s(t), K_f(t)) + C^w(w_a(t), s(t), K_a(t)) \ . \quad (20)$$

The social planner's Hamiltonian is given by:

$$\begin{aligned} H_s(t) = R_s(w_f(t), w_a(t), K_f(t)) - C_s^w(w_f(t), w_a(t), s(t), K_f(t), K_a(t)) - C^I(I_f(t)) - C^I(I_a(t)) \\ + \lambda_s(t)(-w_a(t) - w_f(t) + \gamma(t)) \\ + \lambda_{Kf}(t)(-\delta K_f(t) + I_f(t)) \\ + \lambda_{Ka}(t)(-\delta K_a(t) + I_a(t)) \end{aligned} \ . \quad (21)$$

The social planner's path then follows the following Pontryagin conditions:

$$\begin{aligned}
&[\#1sf]: && \frac{\partial R_f(w_f(t), K_f(t))}{\partial w_f} - \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial w_f} = \lambda_s(t) \\
&[\#1sa]: && \frac{\partial R_a(w_a(t))}{\partial w_a} - \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial w_a} = \lambda_s(t) \\
&[\#1Kf]: && \frac{dC^I(I_f(t))}{dI} = \lambda_{Kf}(t) \\
&[\#1Ka]: && \frac{dC^I(I_a(t))}{dI} = \lambda_{Ka}(t) \ . \qquad (22) \\
&[\#2s]: && \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial s} + \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial s} = \dot{\lambda}_s(t) - r\lambda_s(t) \\
&[\#2Kf]: && \frac{\partial C^w(w_f(t), s(t), K_f(t))}{\partial K_a} + \delta\lambda_{Kf}(t) = \dot{\lambda}_{Kf}(t) - r\lambda_{Kf}(t) \\
&[\#2Ka]: && \frac{\partial C^w(w_a(t), s(t), K_a(t))}{\partial K_a} + \delta\lambda_{Ka}(t) = \dot{\lambda}_{Ka}(t) - r\lambda_{Ka}(t)
\end{aligned}$$

For surface water, the appropriate notion of efficiency is allocative efficiency, whereby water is efficiently allocated if it is allocated to its most valuable uses. The condition for allocative efficiency is that the marginal value of water must be equalized among all uses (Sears and Lin Lawell, 2019). Proposition 1 presents the dynamic analog to this static condition for allocative efficiency that applies to groundwater. All proofs are presented in Appendix B.

Proposition 1: The social planner extracts groundwater for each use in a way that equates the marginal net benefit from each use:

$$MNB_f(w_f(t), s(t), K_f(t)) = MNB_a(w_a(t), s(t), K_a(t)). \tag{23}$$

Proposition 1 shows that for groundwater, the dynamic analog to the static condition for allocative efficiency that in order for water to be allocated to its most valuable uses, and therefore for groundwater extraction to be socially optimal, the marginal net benefit of water should be equalized among both uses: farming and appropriation.

Even in the absence of inefficiencies from property rights based on historical use, there are inefficiencies in the dual rights system because the farmer and the appropriator in a dual rights system each only consider their own private marginal net benefits and private costs of water extraction when making their water extraction and capital investment decisions.

One externality that arises between the farmer and the appropriator in a dual rights system is a *stock effect externality*: water extraction by either the farmer or the appropriator decreases the groundwater stock for both players, and, owing to stock effects in extraction cost, increases the extraction costs of both players.

3.4. Comparing dual rights under open access vs. under historical use

To compare dual rights systems under open access versus under historical use, we make the following functional form assumptions. First, we assume that the per-period revenue $R_f(w_f(t), K_f(t))$ to the farmer that can be generated by producing crops with extracted irrigation water $w_f(t)$ and capital $K_f(t)$, assuming crops are chosen optimally to maximize revenue given extracted irrigation water $w_f(t)$, is given by:

$$R_f(w_f(t), K_f(t)) = p_c(t)\left(K_f(t)\right)^{\kappa} w_f(t), \tag{24}$$

where $p_c(t)$ is the crop price at time *t* and where κ is a non-negative crop production parameter.

We assume that the cost $C^w(w_i(t), s(t), K_i(t))$ of extracting water $w_i(t)$ for both the farmer ($i = f$) and the appropriator ($i = a$) is given by:

$$C^w(w_i(t), s(t), K_i(t)) = c\left(w_i(t)\right)^2 + \left(K_i(t)\right)^d g\left(S - s(t)\right) w_i(t), \tag{25}$$

where S is storage, which we define as the maximum quantity of water that the water table can store, and where c, d, and g are non-negative cost parameters. We also assume that neither the farmer nor the appropriator chooses to invest, and therefore focus on water extraction as the only control variable for each player.

We first examine a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant: $\dot{w}_f(t) = \dot{w}_a(t) = \dot{s}(t) = 0$. Lemma 1 shows that in such a steady-state, the cap in equation (14) on appropriator water extraction under historical use dual rights does not bind, and therefore the non-negative multiplier λ_{wa} on the constraint on appropriator water extraction $w_a(t)$ is equal to 0.

<u>Lemma 1</u>: In a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are constant and fixed at $\bar{w}_f$, $\bar{w}_a$, and $\bar{s}$, respectively, the cap in equation (14) on appropriator water extraction under historical use dual rights does not bind and the non-negative multiplier λ_{wa} on the constraint on appropriator water extraction $w_a(t)$ is therefore equal to 0.

In a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant, the Pontryagin first-order conditions (13) for open access dual rights under our functional form assumptions yield the following conditions:

$$\ddot{p}_c^{OA}(t) = r\dot{p}_c^{OA}(t) \tag{26}$$

$$w_f^{OA} = \frac{rK_f^{\kappa} p_c^{OA}(t) - K_f^{\kappa} \dot{p}_c^{OA}(t) - rgK_f^d (S-s)}{2rc + gK_f^d} \tag{27}$$

$$\ddot{p}_w^{OA}(t) = r\dot{p}_w^{OA}(t) \tag{28}$$

$$w_a^{OA} = \frac{rp_w^{OA}(t) - \dot{p}_w^{OA}(t) - rgK_a^d (S-s)}{2rc + gK_a^d} \tag{29}$$

In a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant, the Pontryagin first-order conditions (17) for historical use dual rights under our functional form assumptions yield the following conditions:

$$\ddot{p}_c^{HU}(t) = r\dot{p}_c^{HU}(t) \tag{30}$$

$$w_f^{HU} = \frac{rK_f^{\kappa} p_c^{HU}(t) - K_f^{\kappa} \dot{p}_c^{HU}(t) - rgK_f^d (S-s)}{2rc + gK_f^d} \tag{31}$$

$$\ddot{p}_w^{HU}(t) = r\,\dot{p}_w^{HU}(t) - \frac{r + 1/\tau}{\tau^2}\lambda_{Wa} \tag{32}$$

$$w_a^{HU} = \frac{rp_w^{HU}(t) - \dot{p}_w^{HU}(t) - \lambda_{Wa}/\tau^2 - rgK_a^d (S-s)}{2rc + gK_a^d} \tag{33}$$

In a similar steady state under socially optimal joint management of water for both appropriation and farming, the Pontryagin first-order conditions (22) for the social optimum yield the following conditions:

$$\dot{p}_w^{SO}(t) = K_f^{\kappa} \dot{p}_c^{SO}(t) \tag{34}$$

$$w_f^{SO} = \frac{r(K_f^{\kappa} p_c^{SO}(t) + gK_f^d (S-s)) - K_f^{\kappa} \dot{p}_c^{SO}(t) + \frac{gK_a^d}{2c}\left(K_f^{\alpha} p_c^{SO}(t) - p_w^{SO}(t) + g(S-s)(K_f^d - K_a^d)\right)}{2rc + g(K_f^d + K_a^d)}$$

(35)

$$w_a^{SO} = \frac{r(p_w^{SO}(t) + gK_a^d(S-s)) - \dot{p}_w^{SO}(t) + \frac{gK_f^d}{2c}\left(p_w^{SO}(t) - K_f^\kappa p_c^{SO}(t) + g(S-s)(K_a^d - K_f^d)\right)}{2rc + g(K_f^d + K_a^d)} \tag{36}$$

Equation (34) implies that in order for a steady state to form in the system under socially optimal management, marginal revenue must grow at the same level for each use. For optimal extraction for farming and appropriation, the terms in equations (35) and (36) can be broken up into components representing the difference in marginal revenue between each use, the difference in the efficiency of extraction due to differences in capital stocks, the current marginal revenue and stock related marginal cost, and the growth in marginal revenue for each use. Extraction for each use grows with its relative superiority in marginal revenue and efficiency in capital stock, while it shrinks as growth in marginal revenue increases. Finally, when stock related costs are high for the given use, its extraction also increases. This reflects the socially optimal balance both between uses and between the present and the future.

Proposition 2 presents a case in which open access dual rights yields the same outcome as historical use dual rights.

Proposition 2: In a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are constant, open access dual rights yields the same outcome as historical use dual rights if the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ is zero.

If the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ is zero, this means that there is no additional value to the appropriator's program from increasing his historical use. Proposition 2 shows that, in a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are constant, if there is no additional value to the appropriator's optimal dynamic program from increasing his historical use, then open access dual rights yields the same outcome as historical use dual rights.

Lemma 2 shows the necessary conditions for a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant under historical use dual rights.

<u>Lemma 2</u>: In a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant under historical use dual rights, either (i) the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ must be zero; (ii) the interval τ over which the moving average of the appropriator's prior pumping is calculated to determine historical use must be infinite, (iii) there are no stock effects ($g = 0$), or (iv) there is no discounting of the future ($r = 0$).

As explained above, condition (i) of Lemma 2 that the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ must be zero means that there is no additional value to the appropriator's program from increasing his historical use. Condition (ii) that the interval τ over which the moving average of the appropriator's prior pumping is calculated is infinite means that the appropriator cannot influence the historical use upon which his cap depends through his water extraction decisions. Condition (iii) that there are no stock effects means that the costs of groundwater extraction do not increase as the groundwater stock is depleted. Condition (iv) that there is no discounting of the future means that the farmer and the appropriator value future periods as much as they do the present.

Thus, Lemma 2 shows that in a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant under historical use dual rights, either (i) there is no additional value to the appropriator's program from increasing his historical use; (ii) the appropriator cannot influence the historical use upon which his cap depends through his water extraction decisions; (iii) the costs of groundwater extraction do not increase as the groundwater stock is depleted; or (iv) the farmer and the appropriator value future periods as much as they do the present.

Proposition 3 shows sufficient conditions under which steady-state extraction is equal to the socially optimal steady-state extraction for both the farmer and the appropriator under open access dual rights, but not under historical use dual rights.

Proposition 3: For a common set of parameters, if a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant exists, then if (i) there are no stock effects ($g = 0$); (ii) the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ is non-zero; and (iii) the interval τ over which the moving average of the appropriator's prior pumping is calculated to determine historical use is finite, then the steady-state extraction is equal to the socially optimal steady-state extraction for both the farmer and the appropriator under open access dual rights, but not under historical use dual rights.

Proposition 3 shows that the steady-state extraction is equal to the socially optimal steady-state extraction for both the farmer and the appropriator under open access dual rights, but not under historical use dual rights, if (i) there are no stock effects; (ii) there is additional value to the appropriator's program from increasing his historical use; and (iii) the appropriator can influence the historical use upon which his cap depends through his water extraction decisions.

The condition of no stock effects is also approximated when either energy prices approach zero, or when the stock of water is full and sufficiently close to the surface. Here, changes in the stock level do little to influence the cost of extraction both in the present and in the future. However, the appropriator may still be limited by the historical use dual rights regime due to his cap on extraction, which forces the appropriator to limit extraction in periods in which it may be cheap, and over-extract in other periods in order to maintain the property right.

Proposition 4 shows conditions under which the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights.

Proposition 4: For a common set of parameters that yields a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant, then:

(1) If the farmer's marginal revenue $p_c(t)K_f^\kappa$ from water extraction is high enough, then the appropriator (i) overextracts (relative to the social optimum) under open access dual rights, and (ii) extracts less under historical use dual rights than under open access dual rights.

(2) If the farmer's marginal revenue $p_c(t)K_f^\kappa$ from water extraction is low enough, then the appropriator (i) underextracts (relative to the social optimum) under both open access dual rights and historical use dual rights, and (ii) underextracts more under historical use dual rights than under open access dual rights.

Proposition 4 shows that under certain values of the farmer's marginal revenue $p_c(t)K_f^\kappa$, the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights. In particular, under a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant, the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights when the farmer's marginal revenue $p_c(t)K_f^\kappa$ is low enough. Thus, the farmer's marginal revenue $p_c(t)K_f^\kappa$ may affect whether open access dual rights yields more or less deadweight loss than historical use dual rights.

When farmer water extraction, appropriator water extraction, and groundwater stock are not constant, a decrease in appropriator water extraction w_a will increase the future groundwater stock s through the equation of motion (9), which, owing to stock effects in extraction costs and the stock effect externality described above, decreases the extraction cost faced by the farmer, and thus, *ceteris paribus*, tends to increase farmer water extraction w_f. Thus, in situations when the appropriator extracts less under historical use dual rights than under open access dual rights, it is possible that the farmer may extract more under historical use dual rights than under open access dual rights, and it may also be more likely that the farmer overextracts relative to the social optimum under historical use dual rights than under open access dual rights, especially if his marginal revenue $p_c(t)K_f^{\kappa}$ from water extraction is particularly high. Thus, once again, the farmer's marginal revenue $p_c(t)K_f^{\kappa}$ may affect whether open access dual rights yields more or less deadweight loss than historical use dual rights.

3.5. Insights from theory model

Our theory model yields several insights. First, our theory model shows that while the socially optimal allocation of groundwater would equate the marginal net benefit of groundwater among farming uses and appropriation uses (Proposition 1), there are inefficiencies in the dual rights system because the farmer and the appropriator in a dual rights system each only consider their own private marginal net benefits and private costs of water extraction when making their water extraction and capital investment decisions. One externality that arises between the farmer and the appropriator in a dual rights system is a *stock effect externality*: water extraction by either the farmer or the appropriator decreases the groundwater stock for both players, and, owing to stock effects in extraction cost, increases the extraction costs of both players.

Second, our theory shows that in certain cases open access dual rights and historical use dual rights both achieve the same level of efficiency. For example, in a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are constant, if there is no additional value to the appropriator's optimal dynamic program from increasing his historical use, then open access dual rights yields the same outcome as historical use dual rights (Proposition 2).

Under certain conditions, however, open access dual rights can be more efficient than historical use dual rights. For example, the steady-state extraction is equal to the socially optimal steady-state extraction for both the farmer and the appropriator under open access dual rights, but not under historical use dual rights, if (i) there are no stock effects; (ii) there is additional value to the appropriator's program from increasing his historical use; and (iii) the appropriator can influence the historical use upon which his cap depends through his water extraction decisions (Proposition 3).

On the other hand, under certain conditions, the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights. For example, under a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant, the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights when the farmer's marginal revenue $p_c(t)K_f^{\kappa}$ is low enough (Proposition 4). Thus, the farmer's marginal revenue $p_c(t)K_f^{\kappa}$ may affect whether open access dual rights yields more or less deadweight loss than historical use dual rights.

4. Application to California

California is experiencing its third-worst drought in 106 years (Howitt and Lund, 2014). While California Governor Jerry Brown officially ended the drought state of emergency in all California counties except Fresno, Kings, Tulare, and Tuolumne in April 2017, the hydrologic effects of the drought will take years to recover (USGS, 2017). From 1960 to the present, there has been significant deterioration in the groundwater level in the Central Valley of California, making current levels of groundwater use unsustainable (Famiglietti, 2014). Groundwater management is particularly important in California as the state produces almost 70 percent of the top 25 fruit, nut, and vegetable crops in the United States (Howitt and Lund, 2014). Most crops in California come from two areas: the Central Valley, including the Sacramento and San Joaquin valleys; and the coastal region, including the Salinas Valley, often known as America's "salad bowl." Farmers in both areas rely heavily on groundwater (York and Sumner, 2015). Understanding the economics of sustainable agricultural groundwater management is particularly timely and important for California as legislation allowing regulation of groundwater is being implemented there gradually over the next several years (York and Sumner, 2015; Sears and Lin Lawell, 2018).

Groundwater users in California can be divided broadly into two types: individual users, usually farmers, who extract water from beneath their own land; and water districts, which combine rights to surface water with appropriated groundwater for use throughout the boundaries of their administrative zones. Under the dual rights system in California, the primary right to groundwater is given to the owner of land "overlying" the resource, while appropriators may divert water that is unused by the overlying user to beneficial uses outside of the land (SWRCB, 2017; Bartkiewicz et al., 2006).

For our numerical analysis, we consider a 50-acre plot of land with a single well at the center. In each period, representing a growing season, the farmer chooses groundwater extraction w_{ft} and the appropriator chooses groundwater extraction w_{at}.

Extracted groundwater w_{ft} is the only source of water for the farmer's irrigation water in our model. This reflects the fact that precipitation in California occurs outside of the growing season for many crops, leaving agriculture primarily reliant on irrigation. Rain therefore affects groundwater extraction decisions through its effect on recharge.

Rain enters our model stochastically as an independent and identically distributed shock each period that is common to both plots. The current value of rain is known to the farmer and the appropriator when they are making water extraction decisions, but future values of rain are uncertain. Our state variables therefore include not only the groundwater stock but also rainfall as well.

Each period, crop production is determined using a simple function of irrigation water w_{ft} and capital K_{ft}. While inputs such as labor or fertilizer affect the yield of the crop, in order to focus the intuition on the water extraction decision we assume that these inputs are used at a fixed level. The farmer has a production technology A, which represents these and other fixed factors related to the plot that affect production, including soil quality. The farmer's revenue is also determined by the price p_c of the crop, which is considered known to the farmer. While exposure to price risk is an area for future research, it lies outside the scope of this paper. Thus, the per-period revenue function for the farmer can be written as:

$$R_{ft}(w_{ft}) = Ap_c(K_{ft})^{\kappa} w_{ft}{}^{\alpha} .$$

We calibrate our model using data from an existing 2016 cost study for a 50-acre alfalfa farm in Tulare County, California (Clark et al., 2016). Tulare County is in the South San Joaquin Valley, which overlies the Central Valley Aquifer system in California. During the production years, the 50-acre Tulare County alfalfa farm in this study uses border flood irrigation. The water is pumped through alfalfa valves at the head of the field and flows down the alfalfa check between the borders. A semi-permanent drain ditch is dug at the edge of the field using a V-Ditcher pulled by a tractor. All field operations turn inside the field and do not cross the drain. From April to

October, 10 irrigations totaling 5.3 acre-feet of water per acre, or 265 acre-feet of water for the entire 50-acre plot, are applied by flooding the checks based on evapotranspiration (ET) requirements. Applied water values are greater than the actual water requirement due to an estimated application efficiency of 75 percent. The actual water requirement will vary each year based on soil, climatic, and plant physiological factors (Sears, Lim and Lin Lawell, forthcoming).

The cost shares of irrigation in production yield an exponent on water extraction in the per-period revenue function to equal $\alpha = 0.3$. We also use the estimates in Clark et al. (2016) of the costs of establishing the crop, the irrigation system, land costs, and the cost of equipment, which total \$871 per acre per year, or \$43,550 for the entire 50-acre plot (Clark et al., 2016). We calibrate our model by assuming that productive capital of \$871 per acre, in combination with the irrigation schedule suggested in the cost study, produce a yield of 10 tons per acre. We can then use total expected production of 500 tons over a 50-acre plot to solve for our baseline $A = 1.31$ using values of $K_{ft} = \$43,550$, an exponent on capital of $\kappa = 0.4$, $w_{ft} = 265$, and $\alpha = 0.3$. This provides us with our baseline production parameters which will be used in simulation. We take the price of alfalfa from Clark et al. (2016), which uses \$250/ton as a baseline value.

The cost function for each plot is composed of two parts: the cost of groundwater extraction and a fixed cost of other inputs. Each plot has a fixed maximum quantity of water that its water table can store, which we call storage S. The cost of water is dependent on both the quantity extracted w_{it} for $i \in \{f, a\}$ and the depth of the water table, which is given by the difference between storage S and the water stock s_t. In our model we use the following cost function:

$$C^w(w_{it}, s_t) = p_e \frac{\lambda}{e}(S - s_t) w_{it} + F,$$

where p_e is the price of electricity (in \$/kwh), $\lambda = 1.551$ is a the amount of electricity (in kwh) required to lift 1 acre-foot of water 1 foot in height (Rogers and Alam, 2006), e represents the efficiency of the irrigation technology, and F represents additional operating costs. We take the price per kwh of electricity from the first 2017 Pacific Gas and Electric (PGE) summer AG-1A rate, a flat rate energy charge used for small agricultural users. The electricity price was \$0.28/kwh at the start of 2017.

Our physical system is calibrated to resemble conditions existing in Tulare County, part of the Central Valley aquifer system in California. For precipitation, we use annual precipitation from

1922-2016 recorded at 6 stations by the California Department of Water Resources to produce discretized probability mass functions for annual rainfall of between 0-4 feet per acre (California Department of Water Resources, 2017d). For transmissivity (or hydroconductivity), we use an average hydrological conductivity value estimated for the Tulare basin of 6.55 feet per day (Williamson et al., 1989). We set the storage S on the plot to be 20 acre-feet per acre, or 1000 acre-feet on the entire 50-acre plot. We assume that water beyond the storage S is either unavailable, or not economical to access either because of the costs of drilling a deeper well, or the costs of extraction.

For appropriators, we assume that the appropriator splits water sales evenly between agricultural and domestic water use. For the baseline water price for appropriators, we use $300 per acre-foot, which is the average of the agricultural water use price and the domestic water use price from the Coachella Valley Water District, an appropriator.[4]

Under our model of historical use dual property rights we incorporate two features commonly used to determine property rights in historical adjudications. First, we allocate a portion of the remaining stock of groundwater as part of the appropriator's property right. This models a right to a share of the "safe yield". Landridge et al. (2016) defines safe yield as "the average quantity of water that can be extracted from an aquifer or groundwater basin over a period of time without causing undesirable results. Undesirable results include permanently lowered groundwater levels, subsidence, degradation of water quality in the aquifer, or decreased stream flow." In our model, we allow the remaining stock that can be economically extracted to proxy for safe yield. Due to the threat of subsidence, and salination in coastal aquifers, safe yield may actually be more complicated in practice to calculate (Landridge et al., 2016). Examples of using shares of safe yield to allocate property rights include the Main San Gabriel adjudication, in which the operating safe yield has been updated over time to reflect changes in monitored water levels and other physical changes to the system, and pumping rights are subsequently updated based on adjudicated

[4] The latest agricultural water use price available is $34.32 per acre-foot, which is the Irrigation Water Commodity charge (Class 1 water used for commercial agricultural activities) effective July 1, 2017 (Coachella Valley Water District, 2017). The latest domestic water use price available is $1.32 per 100 cubic feet, or $574.99 per acre-foot, which is the Tier 2 Efficient water use volumetric/consumptive tiered domestic rate, or the rate charged on water use between 800 cubic feet and 100% of the family's water budget, effective July 1, 2016 (Coachella Valley Water District, 2016). Averaging the two prices, we get $304.65 per acre-foot, which we round to $300 per acre-foot for our baseline appropriator water price.

pumping shares (Landridge et al., 2016). In our baseline calibration we allow the appropriator to have a pumping right to 10 percent of the remaining stock.

The second feature of adjudications that we incorporate into our results is a historical pumping right. This allows the pumping right for the appropriator to be influenced over time by their pumping in each period, creating a "use it or lose it" incentive in which pumpers must make beneficial use of the resource in order to continue to extract it over time. This has been commonly used in historical adjudications, including the Western adjudication in the San Bernardino Valley and Riverside basins, where pumping during a base period was used to determine water rights for a group of plaintiff extractors, and in the Beaumont basin, where a "temporary surplus" was divided among appropriators based on their historical pumping in the five years leading up to the adjudication (Landridge et al., 2016). We incorporate a 5-year moving average of historical extraction to determine this part of the property right in our base case, which echoes the policy used in the Beaumont basin adjudication. Thus, the total pumping right for the appropriator is determined by the sum of these two components:

$$\begin{aligned} & w_{at} \le C_{at} \\ & C_{at} = \delta s_t + \sum_{j=1}^{\tau} \frac{w_{a,t-j}}{\tau} \end{aligned},$$

where, in the base case, the length τ of the historical period used to determine pumping rights equals five years, and the share δ of the stock reserved for the appropriator equals 10 percent.

To solve for the socially optimal coordinated solution, we solve the social planner's dynamic optimization problem in Section 3.3 of choosing water extraction for both the farmer and the appropriator so as to maximize the total expected present discounted value of the entire stream of per-period joint profits for both the farmer and the appropriator. In particular, we solve for the social planner's value function by solving for a fixed point. From Blackwell's Theorem, the fixed point is unique. The value function is the present discounted value of the entire stream of per-period payoffs for each state when the actions are chosen optimally. The solution thus yields the socially optimal coordinated strategy.

To obtain the non-cooperative solution, the equilibrium concept we use is that of a Markov perfect equilibrium. Each player is assumed to play a Markov "state-space" strategy: the past influences current play only through its effect on the state variables. A player's dynamically optimal water extraction policy is then the Markov strategy that it plays in the Markov perfect equilibrium, which is a profile of Markov strategies that yields a Nash equilibrium in every proper subgame (Fudenberg and Tirole, 1998). Our state variables in the numeral simulation are the groundwater stock and rainfall.

We solve for the Markov perfect equilibrium in a game between the farmer and the appropriator, each of whom chooses water extraction to maximize the expected present discounted value of the entire stream of per-period profits from his plot, conditional on the strategy and stock of the other farmer. To solve for the Markov perfect equilibrium, we iterate the set of value functions for both the farmer and the appropriator until the value functions converge to a fixed point and the best response functions converge to a fixed point. In each iteration, we update the strategies of each player such that they represent the best response to the strategy employed by the other player. Convergence of both the value and policy functions thus yields the Markov perfect equilibrium.

In order to estimate the deadweight loss arising from a property rights system, we calculate the difference between the present discounted value of the entire stream of per-period payoffs from the social optimum, and the present discounted value of the entire stream of per-period payoffs from non-cooperative behavior under the respective property rights system. We calculate and compare the deadweight loss from an open access dual rights system, from a historical use dual rights system, and from a single rights system.

Owing to computational constraints, we limit the size of our action space in the simulations by discretizing water extraction into bins of 100 acre-feet each. We allow for the farmer to choose to 100-acre-feet bins of water extraction between 0 and 400 acre-feet of water, representing a range from essentially not planting, to under-watering (or more realistically, reducing the planted acreage), to fully watering (planting and watering the full acreage). We allow for the appropriator to choose to 100-acre-feet bins of water extraction between 0 and 400 acre-feet of water.[5]

[5] We also try a version of the numerical model allowing the farmer and appropriator to choose both groundwater extraction and capital investment. In particular, we allow the farmer to choose between ten levels of groundwater extraction w_{ft} for the growing season and 3 levels of capital investment I_{ft} ; and the appropriator to choose between 5 levels of groundwater extraction w_{at} and 3 levels of capital investment I_{at} . As explained below, our qualitative results are robust to whether we allow the farmer and the appropriator to choose capital investment as well as groundwater extraction. We also find that the players very rarely choose to invest in the scenarios, at a huge cost in computational time and feasibility. We have therefore opted to focus on the water extraction decision rather than both water extraction and capital investment.

Based on our functional form assumptions and baseline parameter values, the marginal revenue that a farmer can receive has a lower bound of \$106.29 per acre-foot and an upper bound of \$280.50 per acre foot. For our discount factor $\beta = \frac{1}{1+r}$, we use a value of 0.9.

Table 1 summarizes our baseline parameter values.

5. Results

According to our theoretical results, even in the absence of a cap on appropriator extraction based on historical use, there are inefficiencies in the dual rights system because the farmer and the appropriator in a dual rights system each only consider their own private benefits and private costs of water extraction when making their water extraction decisions.

Our baseline results, found in Figure 1, show the existence of a deadweight loss due to dual rights in each possible state, with deadweight loss initially rising with the size of the stock. Deadweight loss is highest under a single rights regime, which shows that there is additional value to allowing the appropriation of water in the baseline case. The historical use dual rights regime achieves lower deadweight loss than open access when stock is at a medium level, but actually achieves the same level of efficiency when stock is high, and lower efficiency when stock is low. As seen by the value functions, the farmer tends achieve a higher present discounted value of per-period payoffs under historical use dual rights than under open access, though the policy function for water extraction by the farmer does not differ across the two types of dual rights systems. We see that extraction for farming is highest in the single rights case when stock levels are high. Turning to appropriation, we find that open access encourages extraction for appropriation at lower levels of stock, when water is more expensive to extract, than under the historical use dual rights case. Both dual rights regimes encourage appropriation at lower stocks than the social optimum, and higher extraction for appropriation than the social optimum when stock is high.

Our baseline results show that both dual rights systems encourage the overextraction of water for appropriation when stocks are high, and encourage extraction of water for appropriation when water is relatively expensive. These combine to increase the costs and lower the payoffs to farming, as the farmer cannot maintain a stock of relatively cheap water over the long term.

However, we also find that restricting water from the appropriator has a much higher magnitude efficiency loss, as shown by the deadweight loss from the single rights regime. Overall, the historical rights regime adds little efficiency relative to the open access system, except over a small range of stock levels.

We next allow the price of water for appropriation to vary. This represents cases in which there may be competing municipal demand with higher or lower demand for groundwater. This is a common development in California, where urbanization has rapidly expanded municipal demand for water that had previously been used exclusively for agriculture.

As shown in Figure 2, when the price of water for appropriation is extremely low (at $79.74 per acre-foot), and strictly less than the lower bound of the marginal revenue for the farmer, we find that the single rights regime, in which water is used exclusively for farming, is socially optimal. There is a deadweight loss from both open access and historical use dual rights due to the fact that there is extraction for appropriation under both regimes when stocks are high and water is cheap. The two dual rights regimes actually are equivalent in this case, with both showing deadweight loss that rises with the remaining stock. We find similar results when we allow the price of water to equal the lower bound of marginal revenue for farming, as shown in Figure A1 in Appendix A.

As seen in Figure 3, letting the price of water for appropriation be lower than the baseline, at $225 per acre-foot, which is 25 percent lower than its baseline value, actually brings the historical rights regime into line with the social optimum. Here prices are still high enough that some appropriation is beneficial, however, they are too low for the open access appropriation path to be efficient.

We next set the price of water so that it equals the maximum marginal revenue from farming, or $280.50 per acre-foot. In this case, as seen in Figure 4, the deadweight loss from single rights exceeds that of either dual rights system, and that a single rights system leads the farmer to overextract when stock levels are high, so added value can be gained by allowing the appropriation of water in this case. Both dual rights systems lead to overextraction by the appropriator relative to the social optimum, but the appropriator overextracts relative to the social optimum at high stock levels only in the case of open access. This leads to significant efficiency differences between the two dual rights regimes.

When the price of water for appropriation is strictly greater than the upper bound of marginal revenue from farming, as shown in Figure A2 in Appendix Z, we find that both historical use and open access dual rights lead the appropriator to overextract relative to the social optimum, but the deadweight loss from open access dual rights no longer exceeds that from historical use dual rights by as much.

When we set the price paid to appropriators even higher, at a level 10 percent higher than the baseline in Figure 5, both historical use and open access dual rights still lead the appropriator to overextract relative to the social optimum, but now there is a range of low stock levels in which open access actually outperforms historical rights.

We next vary the price of crops. This allows us to see the effects of having higher value crops in the model. Alfalfa is a relatively low value crop compared to others that are grown in California.

An implication of Proposition 4 of our theory model is that in situations when the appropriator extracts less under historical use dual rights than under open access dual rights, it is possible that the farmer may extract more under historical use dual rights than under open access dual rights, and it may also be more likely that the farmer overextracts relative to the social optimum under historical use dual rights than under open access dual rights, especially if his marginal revenue $p_c(t)K_f^{\kappa}$ from water extraction is particularly high. Letting the price of crops be 5 percent higher in Figure 6, which raises the farmer's marginal revenue from water extraction, we find that the farmer under historical rights now extracts at a higher level when stock is high, while the open access farmer remains in line with the social optimum. This leaves less value for appropriation, leading to much higher deadweight loss under historical use dual rights than under open access dual rights when stock is high.

As seen in Figure A3 in Appendix A, lowering the price of crops by 50 percent causes the farmer to not plant at low stock levels in all regimes, and to plant at lower stock levels in open access, and slightly higher levels under historical rights. However planting still takes place at levels of stock below the social optimum level under dual rights regimes. Here the inability to substitute toward appropriation creates high inefficiency under single rights.

Our next approach varies the shares of capital and water in production for farming. This has the effect of raising or lowering the marginal product of both capital and water for a given set of inputs. In Figure A4 in Appendix A, in which we set the share of capital in crop production to be 100 percent higher than baseline, we find that more capital intensive crops leads to higher farmer extraction than the baseline. We also find that appropriation is high under both dual rights regimes, despite not being socially optimal at any level of stock. This reflects groundwater's common pool property, as both dual rights regimes allow for competition for the resource, and this competition is highest under open access where extraction is unrestricted. Thus, even though the appropriator's conditions have not changed, they extract at a higher level when faced with more competition from the farmer. This reflects a strategic externality. As a result there are high efficiency loss under each regime, with the highest occurring under open access when stock is high.

As shown in Figure 7, when we allow the capital share to be lower, at a level that is 75 percent lower than baselin, which lowers the marginal product from farming, we find that the farmer's essentially exits, and does not extract any groundwater under any stock level. In this case, there is very little deadweight loss from either dual rights systems, and the historical use dual rights system approximates the social planner's outcome. Thus, a lower share of capital in crop production reduces the inefficiency from a dual rights system.

Letting the share of water in crop production vary similarly raises and lowers the marginal product of both capital and water for a given set of inputs. As seen in in Figure A5 in Appendix A, which sets the share of water in crop production to be 200 percent higher than basline, we find that more water intensive crops lead to equal farming extraction under each regime, and increases competition for the resource by the appropriator. Allowing the share of water in production to be lower leads to no extraction for farming at low stock levels, as seen in Figure A6 in Appendix A, which sets the share of water in crop production to be 50 percent lower than baseline. However, water is extracted for farming at lower stock levels than is efficient under each of the dual rights regimes, creating deadweight loss. This makes appropriation at high stock levels optimal again, and lowers the water demands of farming in each regime.

We next allow the technology of crop production A to vary. As seen in Figure A7 in Appendix A, we find that more productive technology leads to overextraction when stocks are high under both the single rights and the historical rights regimes. Here appropriation is again inefficiently high under both regimes due to increased competition for resources with the farmer. Again, historical rights is outperformed by open access. When the technology is less effective (Figure A8 in Appendix A), we find that there is still overextraction for farming under dual rights, but now it occurs at lower levels of the stock rather than high, and is more pronounced under open access. Overextraction for appropriation occurs at high stock levels, and starts at a lower stock level under open access.

We next vary the price of electricity. This makes extraction more or less costly at a given level of the water stock. As seen in Figure 8, since higher electricity prices increase the cost of extraction, the farmer no longer overextracts relative to the social optimum under historical use dual rights, and only overextracts under open access dual rights when the groundwater stock is low. The appropriator extraction is actually mostly aligned with the social optimum under dual rights. Except when stock levels are low under open access dual rights, a high electricity price reduces the inefficiencies that arise from a dual rights system.

In contrast, lowering the price of electricity leads to farming overextraction at high levels of stock, and overextraction for appropriation (Figure A9 in Appendix A). Here the two property rights regimes perform similarly.

We next perturb the distribution of precipitation. As shown in Figure A10 in Appendix A, we find that extraction by the farmer is generally optimal, except when stocks are high, in which case single rights leads to over-extraction. The appropriator though overextracts as stock increases relative to the social optimum especially under open access. Eliminating the possibility of drought brings single farmer rights use above the social optimum at high levels of stock, and leads to over extraction under both dual rights regimes for appropriation (Figure A11 in Appendix A). In Figure A12, we allow the probability of extreme weather to rise on either side. This leads to inefficiently high extraction for appropriation under both dual rights regimes. In Figure A13, we find that substantially raising the probability of drought again leads to inefficiently high appropriation at high stock levels. Thus, we find that climate scenarios lead the two dual rights regimes to closer results, with most inefficiency created by overextraction for appropriation. We also find a common issue of overextraction for farming under a single rights regime.

We next allow the parameters governing the historical property rights regime to vary. First, in Figures A14 and A15 in Appendix A we raise and then lower the value of the share δ of the stock allocated to the appropriator, respectively. First, raising the share δ to 20 percent leads to an equivalence between the historical pumping rights regime and open access. Lowering the share δ to 6 percent leads to lower extraction by the appropriator under historical rights when stocks are high, which is inline with the social optimum. Thus, lowering this stock based share increases efficiency relative to the baseline. This is likely due to the fact that higher shares of the remaining stock increase the property right even when stocks are low, while a smaller share only impacts the property right in a significant way when stocks are high, which may incentivize the appropriator to conserve water when stocks are high.

Finally, we vary τ , the length of the period used to determine the historical pumping right. In Figure A16 in Appendix A we raise the length of the period to 10 years, and find that pumping by the appropriator now starts at lower levels of stock, when water is more expensive. This leads to less efficient outcomes under historical rights when stocks are relatively low. In Figure A17 in Appendix A we lower the length of the period to just the previous year. We find that this produces similar results under historical rights to open access. Shorter historical rights periods provide less security for the appropriator, since the appropriator must pump in each period in order to maintain this part of their property right. This leads to extraction at lower levels of stock by the appropriator. Raising the length of the period decreases the effect of pumping in each period on the future pumping right. This leads to a shift in pumping by the appropriator, in which pumping starts at lower levels of stock, but does not monotonically increase with the stock.

We also ran a version of the numerical model allowing the farmer and appropriator to choose both groundwater extraction and capital investment, and incorporating an investment cost. Our qualitative results are robust to whether we allow the farmer and the appropriator to choose capital investment as well as groundwater extraction. We also find that the players very rarely choose to invest in the scenarios, at a huge cost in computational time and feasibility. For example, under the base case parameters, no capital investment by either the farmer or the appropriator took place in either the social optimum, single rights, historical use dual rights, or open access dual rights. We have therefore opted to focus on the water extraction decision rather than both water extraction and capital investment.

6. Conclusion

Groundwater is both a valuable input to high value agriculture, and a secure supply of drinking water for municipalities in California (Sears et al., 2018). As a common pool resource, groundwater resources are susceptible to being used in a socially inefficient manner over time and space. As a result, groundwater resources have suffered long-term declines, due to extraction exceeding recharge in arid regions. Unfortunately, these arid regions are also home to some of California's most important agricultural regions and population centers (Sears and Lin Lawell, 2019).

One possible mechanism that could be used to bring extraction in line with efficient levels is through formalizing markets for groundwater in California. A necessary component of instituting these markets is the quantification of property rights for groundwater. Groundwater property rights in California are governed by a dual rights system, in which the primary right to groundwater is given to the owner of land "overlying" the resource, while appropriators may divert water that is unused by the overlying user to beneficial uses outside of the land. Historically, groundwater rights have been quantified through court adjudications. While methods vary, courts have frequently used historical pumping as a basis upon which groundwater rights are allocated.

In this paper, we develop a theory of dual rights to groundwater, and evaluate the inefficiencies that arise both analytically and numerically. In particular, we use a combination of dynamic programming, optimal control theory, and game theory to analyze a dual rights system and compare it to a single rights system and to the social optimum. We then make theoretical predictions about the optimal path of water use in California, and how imperfections in the property rights system governing groundwater may impact its use over time.

Our results show that a dual rights system can be inefficient and lead to deadweight loss and the overextraction of water. There are several sources of inefficiency in a dual rights system. First, while the socially optimal allocation of groundwater would equate the marginal net benefit of groundwater among farming uses and appropriation uses, there are inefficiencies in the dual rights system, even in the absence of inefficiencies from property rights based on historical use, because the farmer and the appropriator in a dual rights system each only consider their own private marginal net benefits and private costs of water extraction when making their water extraction and capital investment decisions.

Second, historical use dual property rights incentivize over-extraction when property rights in the future have value. The possibility of use it or lose it rights may lead to inefficiently high extraction. The possibility of gaining large water rights for the future may also lead to inefficient extraction. Historical use property rights can even lead to less efficient outcomes than open access to the resource. By allowing water rights to be based on past pumping, this regime incentivizes inefficient pumping by appropriators in some cases.

Third, groundwater is a common pool resource. As a consequence, the farmer and appropriator compete for the same limited resource, leading to inefficient overextraction. In some of the scenarios examined, the inefficiencies arising from the common pool resource is particularly acute when the groundwater stock is low, as the farmer and appropriator overextract as they compete for the scarce resource.

A fourth source of inefficiency in a dual rights system arises because the farmer and the appropriator faces a different marginal revenue from water extraction. While the farmer uses the water for crops and therefore faces a marginal revenue arising from crop production, the appropriator faces a water price. The water price faced by the appropriator may differ from the marginal revenue arising from crop production because the water price is determined by competing demands from municipal water demand, reflecting demand from residential and/or industrial water use, as well as agricultural water demand. In addition, farmers may not have access to markets for water or markets for water rights. The water price faced by the appropriator may also reflect any inability of users to access a market for water, or to sell their rights, and therefore may diverge from the farmer's marginal revenue for that reason as well.

Our theory model shows that in certain cases open access dual rights and historical use dual rights both achieve the same level of efficiency. However, under certain conditions, open access dual rights can be more efficient than historical use dual rights. On the other hand, under certain conditions, the appropriator's water extraction may deviate more from the social optimum under historical use dual rights than under open access dual rights.

According to the results of our numerical application to California, we find that in general, players alter their behavior over the margin of water extraction in response to changes in the level of groundwater stock and the parameters governing the system. Our results indicate that a single rights regime, in which water is reserved only for farming severely limits the total value of the resource, indicating that appropriation adds significant value. However, when prices are significantly more in favor of farming than appropriation, it may be optimal to restrict water access from appropriators.

Our results show that the inefficiency from a dual rights system can be reduced if the price of water for appropriation is low, if the price of electricity is high, and also if the share of capital in production is low.

We also find that the historical use dual rights regime generally performs similarly to open access dual rights and that the main differences occur due to the restriction placed upon the appropriator. In some cases, the cap on appropriator extraction under historical use dual rights limits overextraction by the appropriator under historical use. On the one hand, this limits competition for the resource and can lead to less extraction by the farmer at high and low levels of stock, which in turn allows the appropriator to avoid extraction when stock is low and costs are high. On the other hand, this also can lead to more aggressive farmer response to high crop prices, and thus may produce more inefficient results than even open access. Considering the costs of administering an historical use dual rights system are likely positive, while an open access system has no costs, this shows that historical use dual rights systems can lead to large inefficiencies, even relative to not regulating the resource.

Our results have important implications for the design of property rights regimes and water management policies for groundwater.

References

Ayres, A.B., K.C. Meng, and A.J. Plantinga. (2018). The economic value of secure water: Landowner returns to defining groundwater property rights. Working paper, University of California at Santa Barbara.

Bartkiewicz, P., S. Kronick, R. Shanahan, A. Lilly, R. Bezerra, J. Horowitz, Y. West, and J. Boyd Jr. (2006). A Summary of the California Law of Surface Water and Groundwater Rights. Report for the Northern California Water Association. URL: https://www.norcalwater.org/wp-content/uploads/bks_water_rights.pdf

Browne, O. (2018). The economic value of clarifying property rights: Evidence from water in Idaho's Snake River Basin. Working paper, University of Chicago.

California Department of Water Resources [DWR]. (2003). DWR Bulletin 118: Appendices. URL: http://www.water.ca.gov/pubs/groundwater/bulletin_118/california's_groundwater__bulletin_118_-_update_2003_/bulletin118-appendices.pdf

California Department of Water Resources [DWR]. (2017). Groundwater Sustainability Agencies. URL: http://www.water.ca.gov/groundwater/sgm/gsa.cfm

California State Water Resources Control Board. (2011). The History of the Water Boards: The Early Years of Water Rights. URL: http://www.swrcb.ca.gov/about_us/water_boards_structure/history_water_rights.shtml

California Water Code Section 1005, 1-4. Definitions and Interpretations of Divisions. URL: http://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=WAT&division=2.&title=&part=1.&chapter=1.&article=

Clark, N., C.A. Frate, D.A. Sumner, K. Klonsky, D. Stewart, and C.A. Gutierrez. (2016). Sample Costs to Establish and Produce Alfalfa: Tulare County, Southern San Joaquin Valley. University of California Agricultural Issues Center. URL: https://coststudyfiles.ucdavis.edu/uploads/cs_public/24/b6/24b68b4a-4c04-4853-b127-d3461e1a248f/16alfalfasjv50ac_final_4192016.pdf

Coachella Valley Water District. (2016). Domestic Water Rates. URL: http://www.cvwd.org/DocumentCenter/View/897/Domestic-Water-Rates-PDF?bidId=

Coachella Valley Water District. (2017). Canal Water Rates and Charges. URL: http://www.cvwd.org/DocumentCenter/View/895/Canal-Water-Service-Rates-PDF?bidId=

Famiglietti, J. (2014). Epic California drought and groundwater: Where do we go from here? *National Geographic*, 4 February 2014. URL: http://voices.nationalgeographic.com/2014/02/04/epic-california-drought-and-groundwater-where-do-we-go-from-here/

Fitzgerald, T. (2010). Evaluating split estates in oil and gas leasing. *Land Economics*, 86 (2), 294–312.

Fudenberg, D., and J. Tirole. (1998). *Game Theory*. Cambridge: MIT Press.

Grossman, H.I. (2001). The creation of effective property rights. *American Economic Review*, 91 (2), 347–352.

Howitt, R., and J. Lund. 2014. Five myths about California's drought. *Washington Post*, 29 August 2014.

Lambert, D. (1984). District management for California's groundwater. *Ecology Law Quarterly*, 11 (3), 373-400.

Langridge, R., A. Brown, K. Rudestam, and E. Conrad. (2016). An Evaluation of California's Adjudicated Groundwater Basins. Report for the State Water Resources Control Board. URL: https://www.waterboards.ca.gov/water_issues/programs/gmp/docs/resources/swrcb_012816.pdf

Lin Lawell, C.-Y.C. (2016). The management of groundwater: Irrigation efficiency, policy, institutions, and externalities. *Annual Review of Resource Economics*, 8, 247-259.

Lin Lawell, C.-Y.C. (2018). Property rights and groundwater management in the High Plains Aquifer. Working paper, Cornell University.

Lustgarten, A. (2015). Amid drought, Califrornia experiments with leasing water rights. *ProPublica*, 1 August 2015. URL: https://www.propublica.org/article/amid-drought-california-experiments-with-leasing-water-rights

Pfeiffer, L., and C.-Y.C. Lin. (2012). Groundwater pumping and spatial externalities in agriculture. *Journal of Environmental Economics and Management*, 64 (1), 16-30.

Rogers, D.H., and M. Alam. (2006). Comparing Irrigation Energy Costs. Irrigation Management Series. Kansas State University: Agricultural Experiment Station and Cooperative Extension Service. Manhattan, Kansas. URL: https://www.bookstore.ksre.ksu.edu/pubs/MF2360.pdf

Schlager, E., and E. Ostrom. (1992). Property-rights regimes and natural resources: A conceptual analysis. *Land Economics*, 68 (3), 249-262.

Sears, L., J. Caparelli, C. Lee, D. Pan, G. Strandberg, L. Vuu, and C.-Y.C. Lin Lawell. (2018). Jevons' Paradox and efficient irrigation technology. *Sustainability*, 10 (5), 1590.

Sears, L., D. Lim, and C.-Y.C. Lin Lawell. (2017). Agricultural groundwater management in California: Possible perverse consequences? *Agricultural and Resource Economics Update*, 20 (3), 1-3.

Sears, L., D. Lim, and C.-Y.C. Lin Lawell. (2018). The economics of agricultural groundwater management institutions: The case of California. *Water Economics and Policy*, 4 (3), 1850003.

Sears, L., D. Lim, and C.-Y.C. Lin Lawell. (forthcoming). Spatial groundwater management: A dynamic game framework and application to California. *Water Economics and Policy*.

Sears, L., and C.-Y.C. Lin Lawell. (2018). Property rights and groundwater management: A dynamic structural model of the dual rights system in California. Working paper, Cornell University.

Sears, L., and C.-Y.C. Lin Lawell. (2019). Water management and economics. In G.L. Cramer, K.P. Paudel, and A. Schmitz (Eds.), *The Routledge Handbook of Agricultural Economics* (pp. 269-284). London: Routledge.

State Water Resources Control Board [SWRCB]. (2017). The Water Rights Process. URL: http://www.waterboards.ca.gov/waterrights/board_info/water_rights_process.shtml

Sweeney, R.J., R.D. Tollison, and T.D. Willett. (1974). Market failure, the common-pool problem, and ocean resource exploitation. *Journal of Law & Economics*, 17 (1), 179-192.

Tsvetanov, T., and D. Earnhart. (2018). The effectiveness of a water right retirement program at conserving water. Working paper, University of Kansas.

U.S. Geological Survey [USGS]. (2017). California Drought. URL: https://ca.water.usgs.gov/data/drought/

Wallander, S. (2017). USDA water conservation efforts reflect regional differences. *Choices*, 32 (4).

Williamson, A., D. Prudic, and L. Swain. (1989). Ground-water flow in the Central Valley, California. Regional Aquifer-System Analysis: Central Valley, California. U.S. Geological Survey Professional Paper 1401-D. URL: https://pubs.usgs.gov/pp/1401d/report.pdf

York, T., and D.A. Sumner. (2015). Why food prices are drought-resistant. *Wall Street Journal*, 12 April 2015.

Zilberman, D., R. Taylor, M.E. Shim, and B. Gordon. (2017). How politics and economics affect irrigation and conservation. *Choices*, 32 (4).

Table 1: Baseline parameter values

	Value	Source
Crop	Alfafa	
County	Tulare	
Aquifer System	Central Valley	
Yield	10 tons per acre	Clark et al. (2016)
Cost of water	$130 per acre-foot	Clark et al. (2016)
Quantity of water	5.3 acre-feet per acre	Clark et al. (2016)
Cost of capital	$871 per acre	Clark et al. (2016)
Exponent α on water	0.3	
Exponent κ on capital	0.4	
Crop price	$250/ton	Clark et al. (2016)
Irrigation efficiency	75%	Clark et al. (2016)
Establishment/planting cost	$0	
Transmissivity (or hydroconductivity)	6.55 ft/day	Williamson et al. (1989)
Storage	20 acre-feet per acre	
Precipitation	Tulare	California Department of Water Resources (2017d)
Electricity price	$0.28/kwh	2017 Pacific Gas and Electric summer AG-1A rate
Water price for appropriator	$300 per acre-foot	Coachella Valley Water District (2016, 2017)
Length τ of the historical period used to determine pumping rights	5 years	Landridge et al. (2016)
Share δ of the stock reserved for the appropriator	10%	
Discount factor β	0.9	

Figure 1: Baseline results

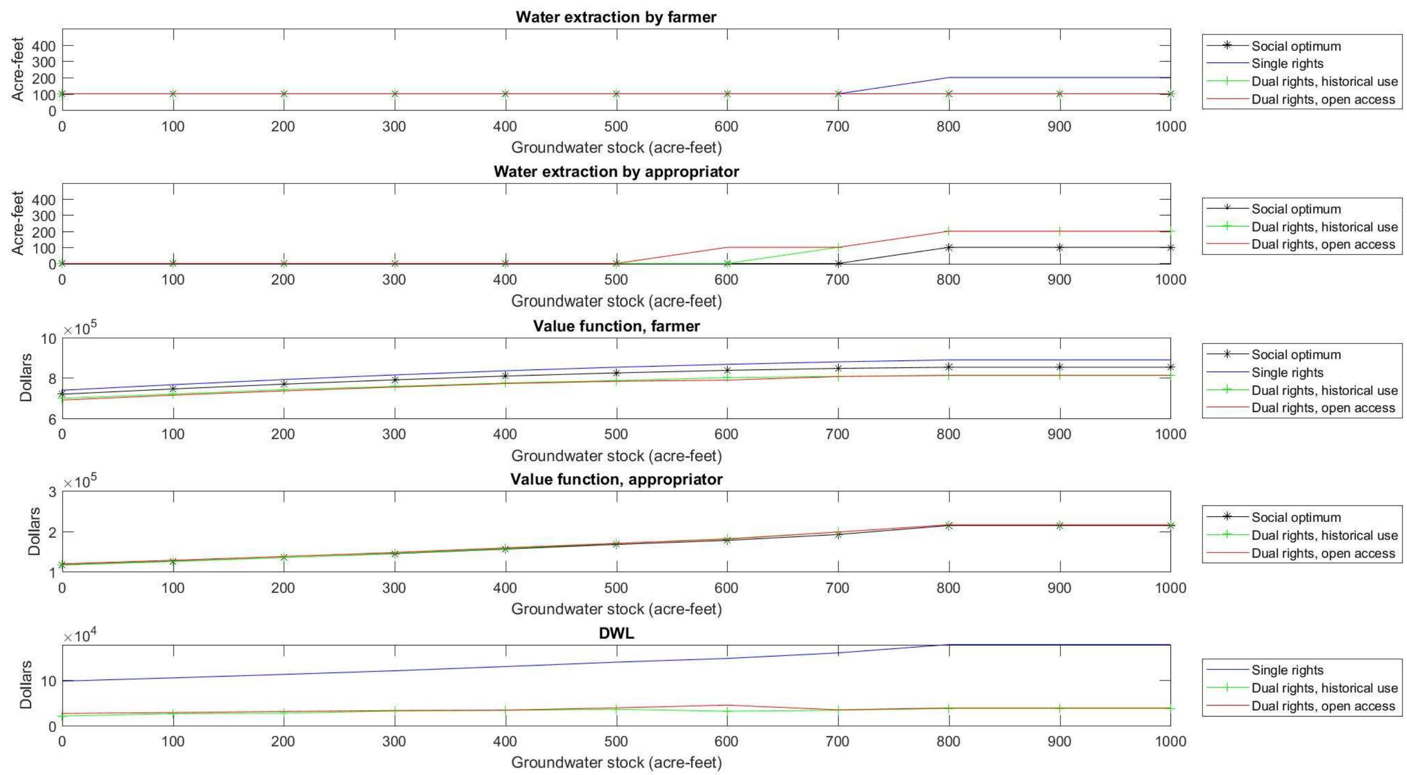
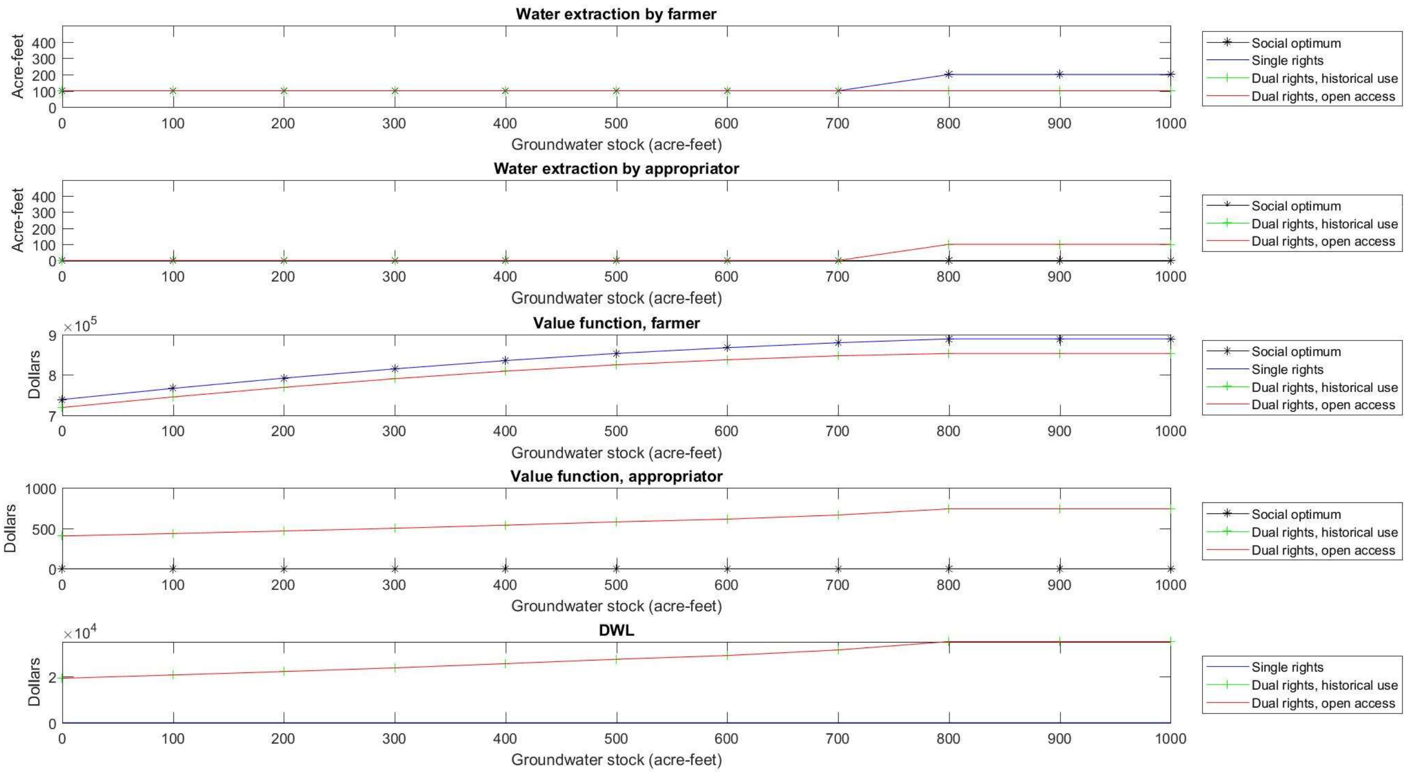
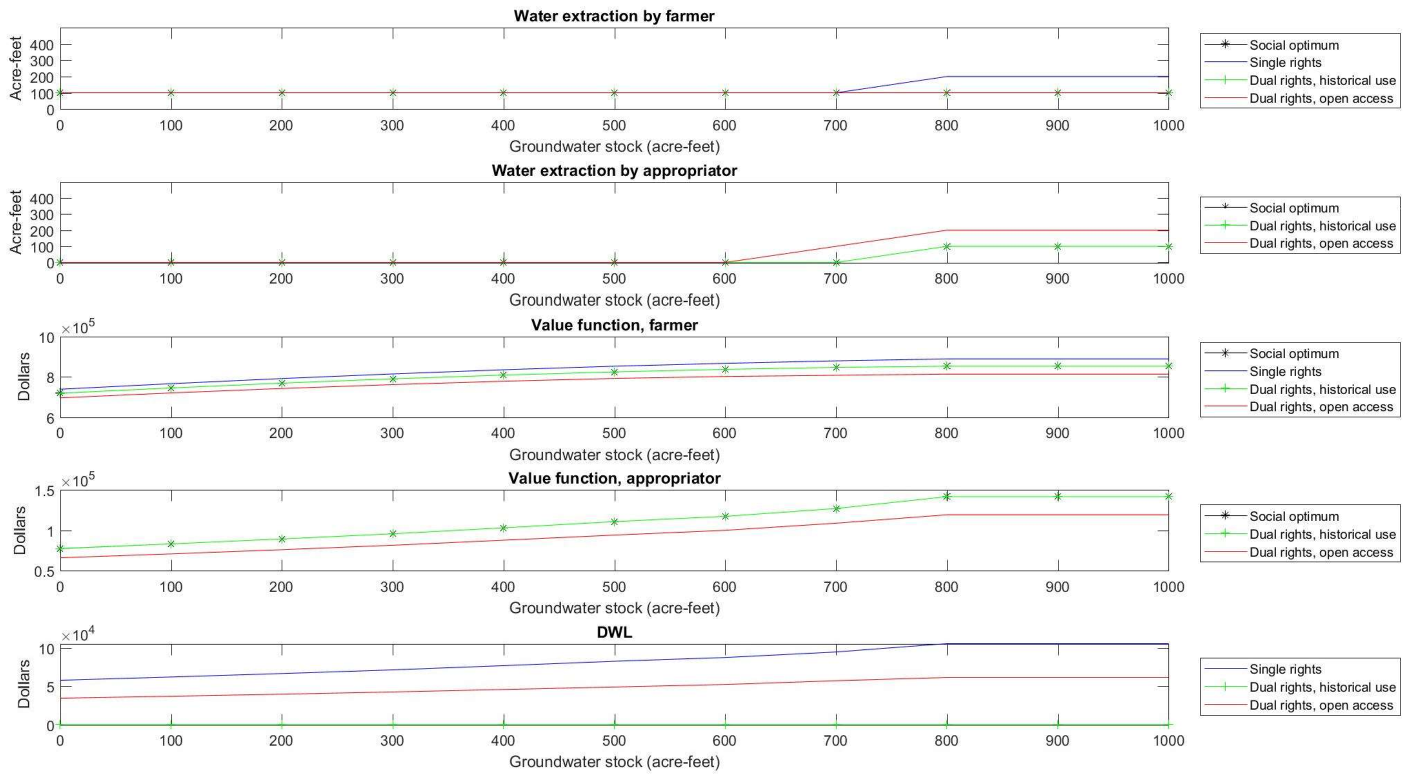


Figure 2: Price of water for appropriator is less than lower bound of marginal revenue for farmer



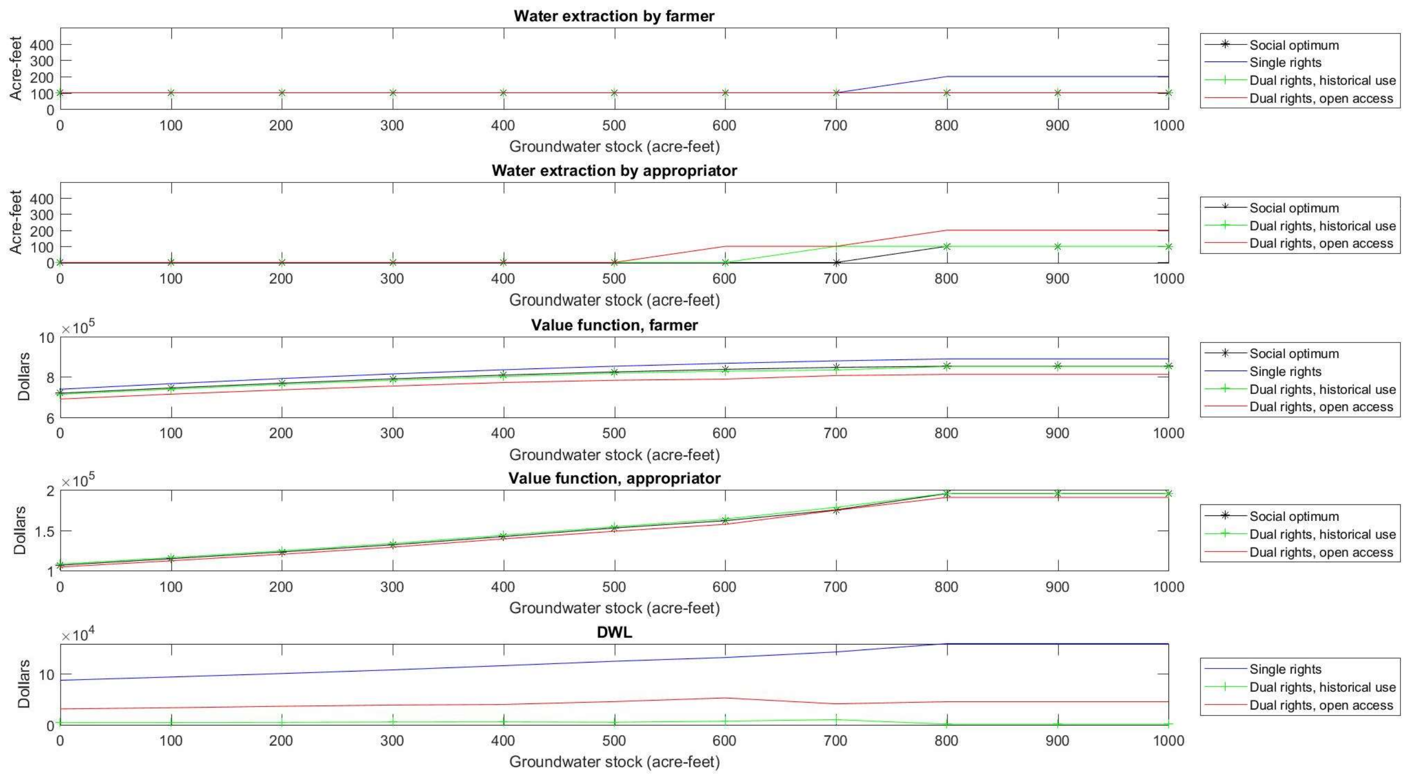
Note: In this scenario, the appropriator water price is $79.74 per acre-foot.

Figure 3: Price of water is low (75% of baseline price of water)



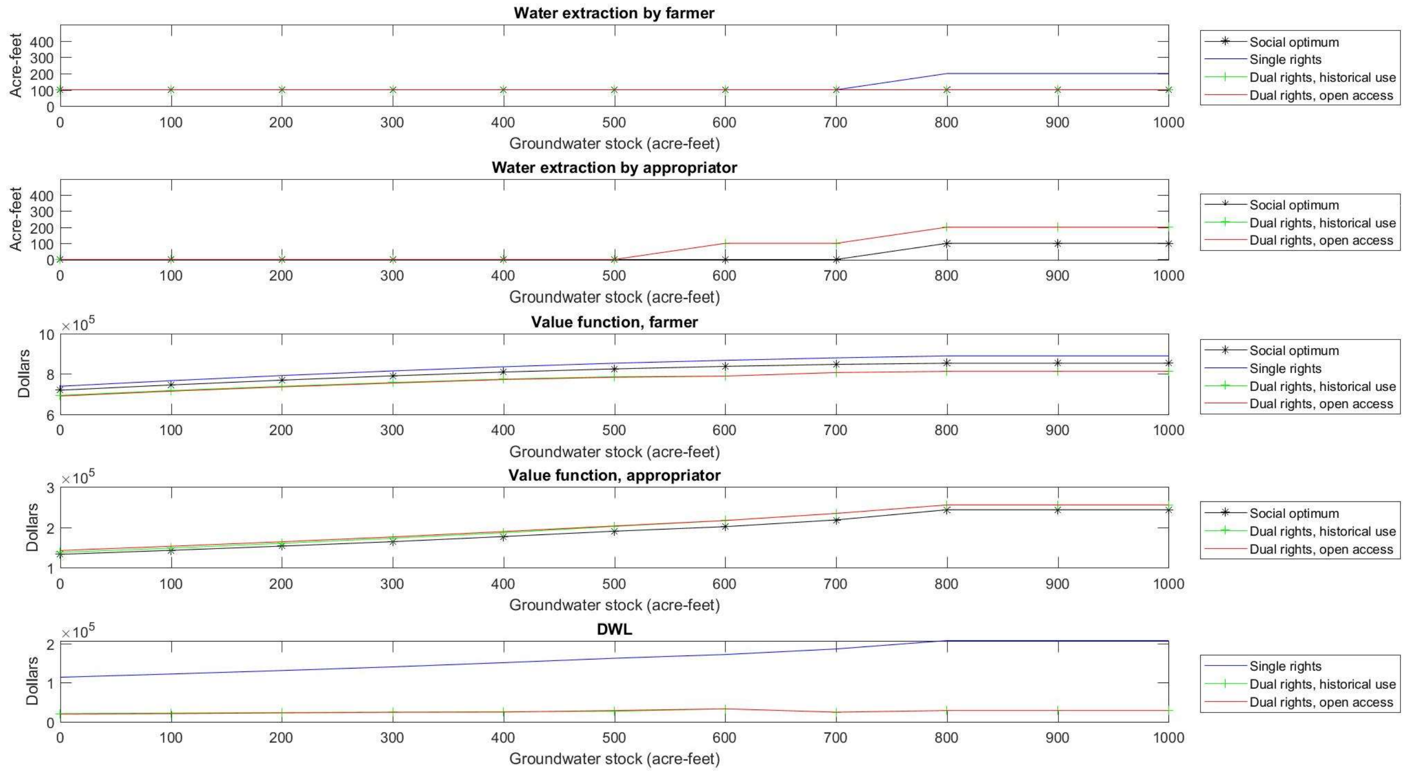
Note: In this scenario, the appropriator water price is $225 per acre-foot.

Figure 4: Price of water for appropriator equals upper bound of marginal revenue for farmer



Note: In this scenario, the appropriator water price is $280.50 per acre-foot.

Figure 5: Price of water is 110% of baseline



Note: In this scenario, the appropriator water price is $330 per acre-foot.

Figure 6: Price of crop is 105% of baseline

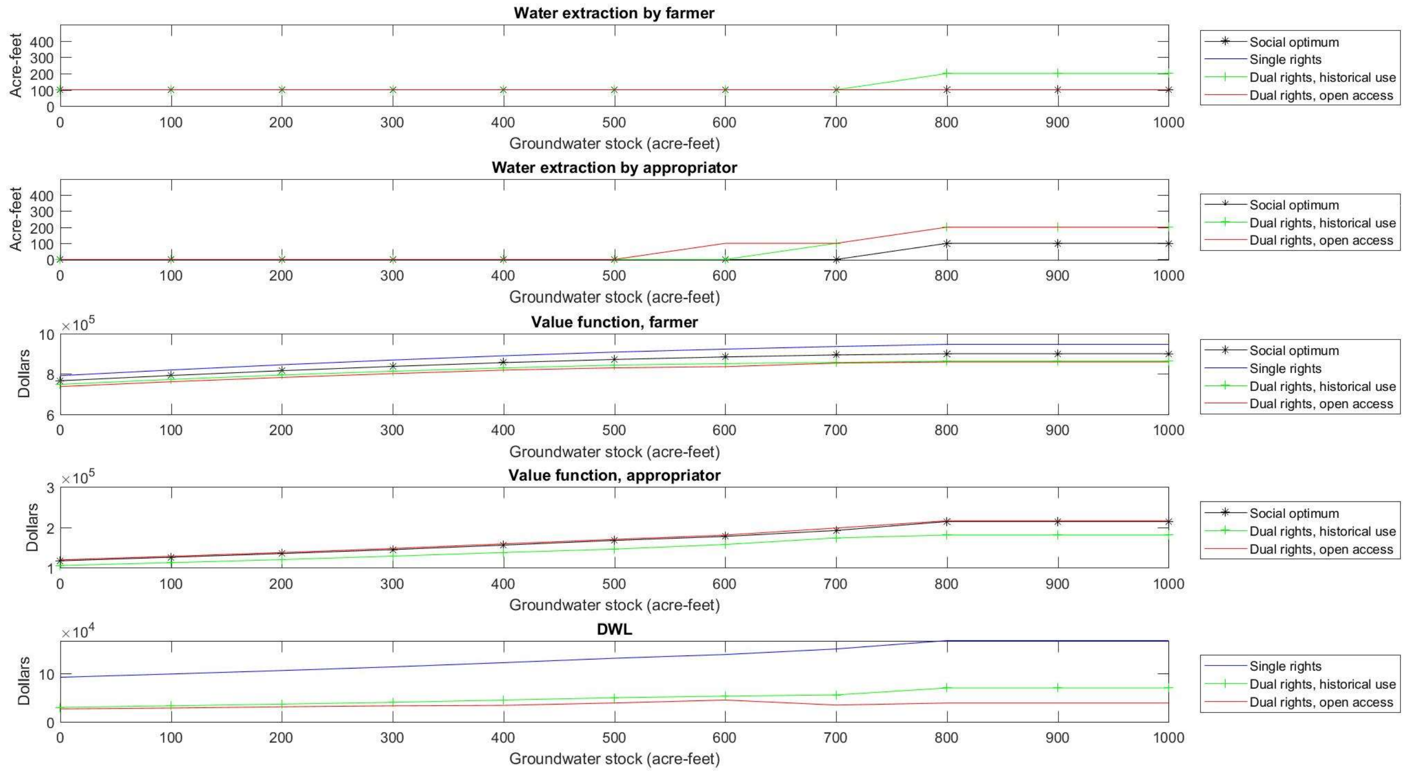


Figure 7: Share of capital in crop production is 25% of baseline

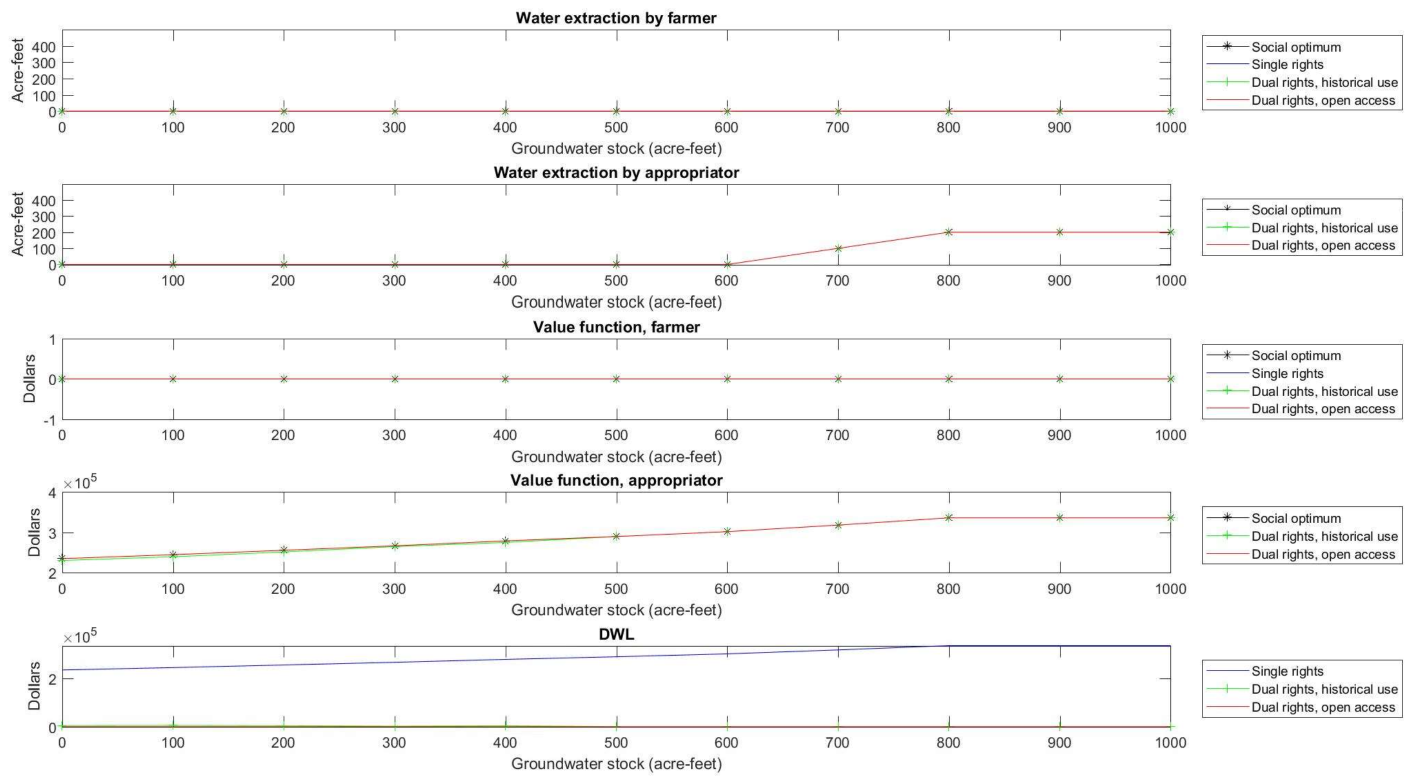
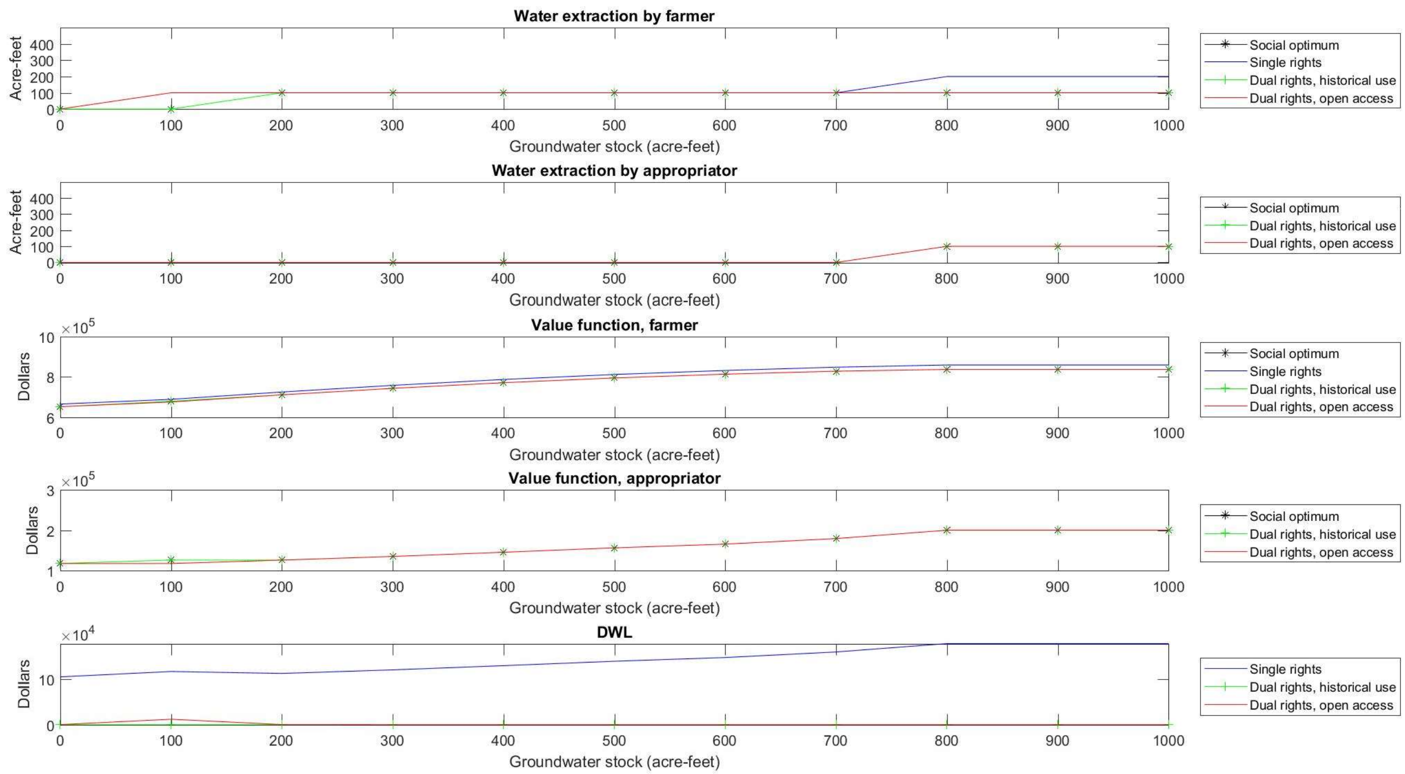


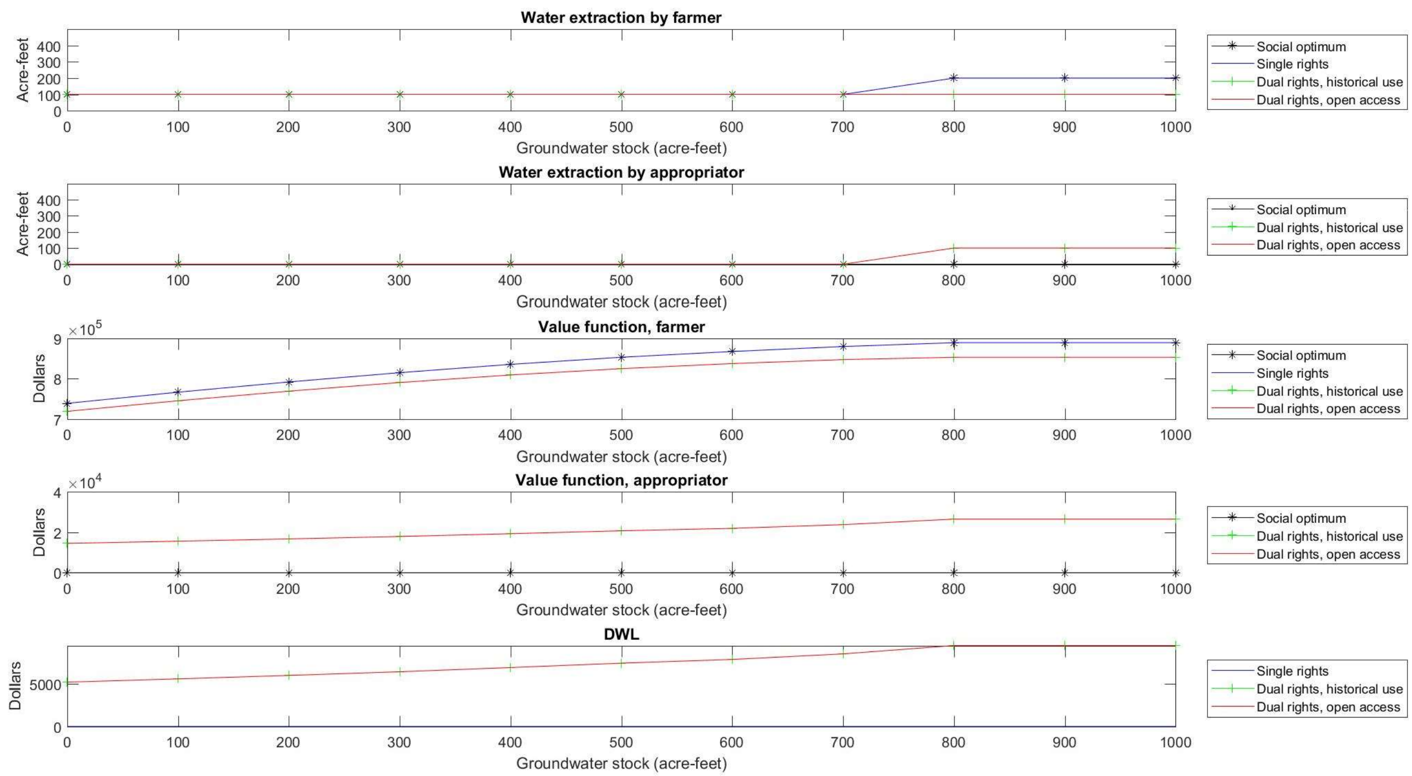
Figure 8: Price of electricity is 150% of baseline



Appendix

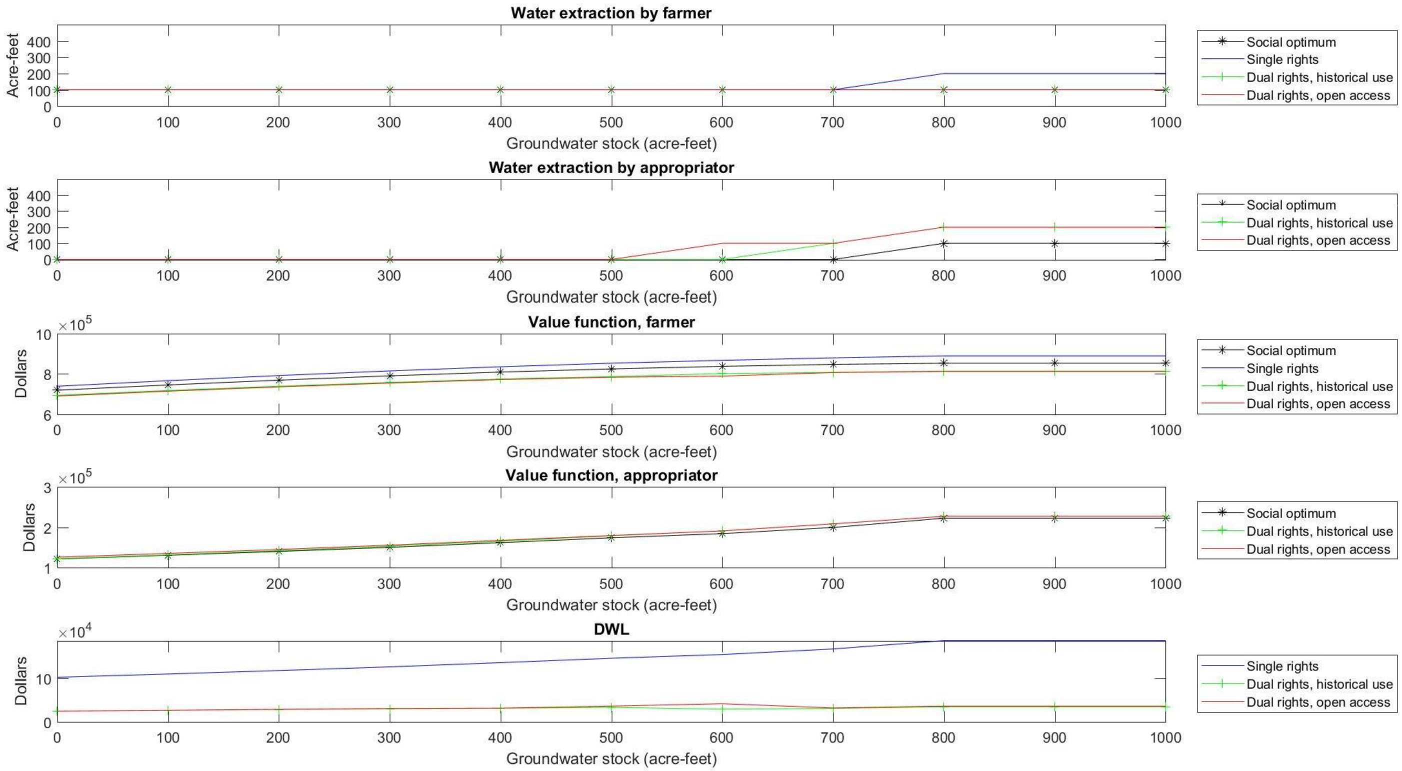
Appendix A. Supplementary Figures

Figure A1: Price of water for appropriator equals lower bound of marginal revenue for farmer



Note: In this scenario, the appropriator water price is $106.29 per acre-foot.

Figure A2: Price of water for appropriator is greater than upper bound of marginal revenue for farmer



Note: In this scenario, the appropriator water price is $308.55 per acre-foot.

Figure A3: Price of crop is 50% of baseline

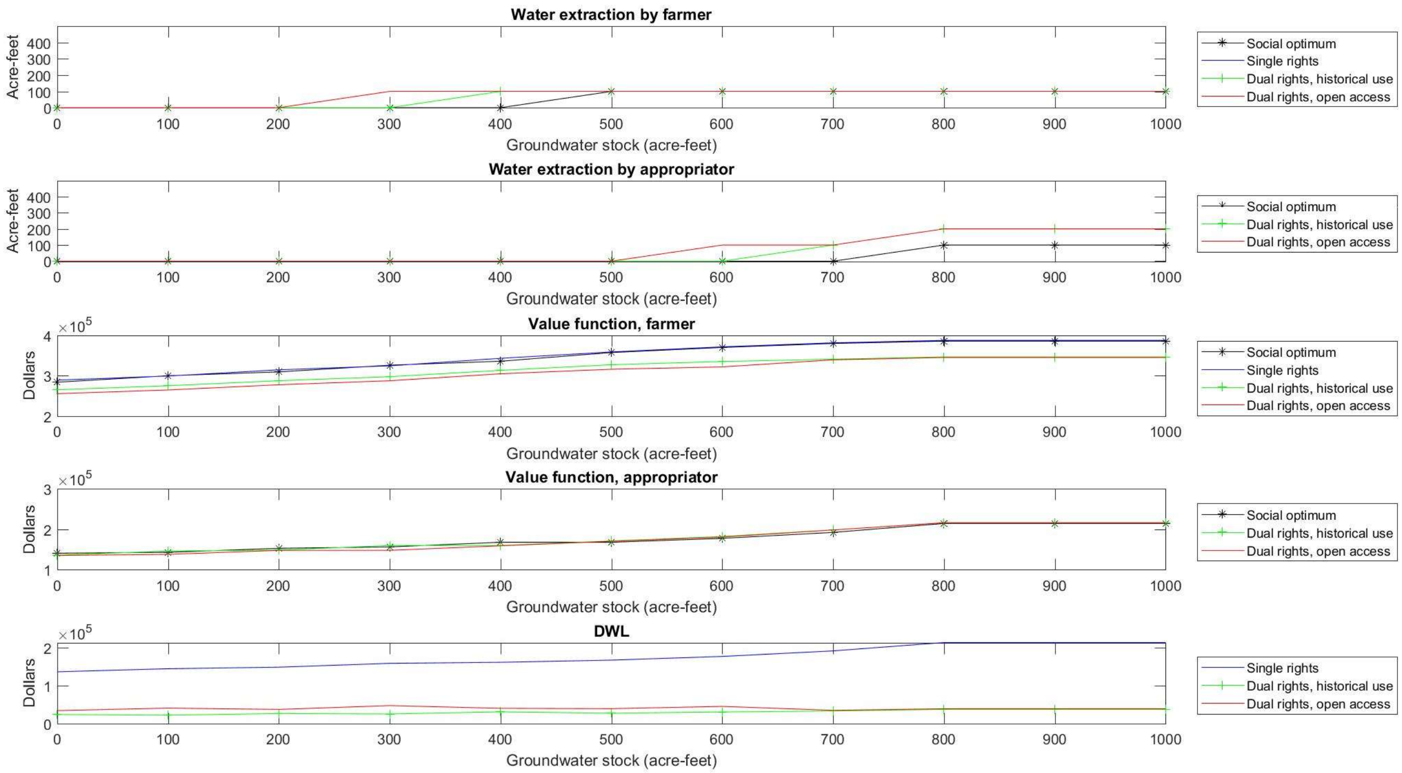


Figure A4: Share of capital in crop production is 200% of baseline

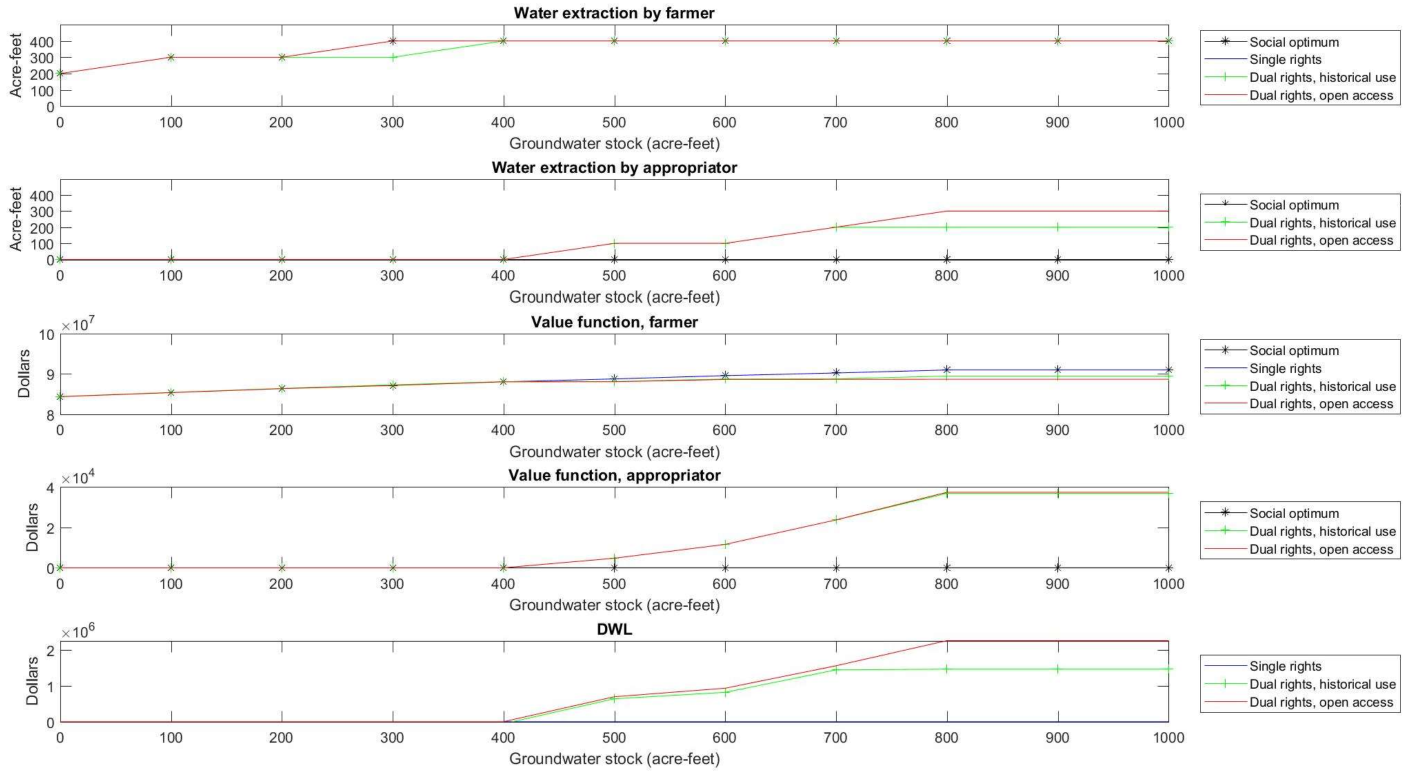


Figure A5: Share of water in crop production is 300% of baseline

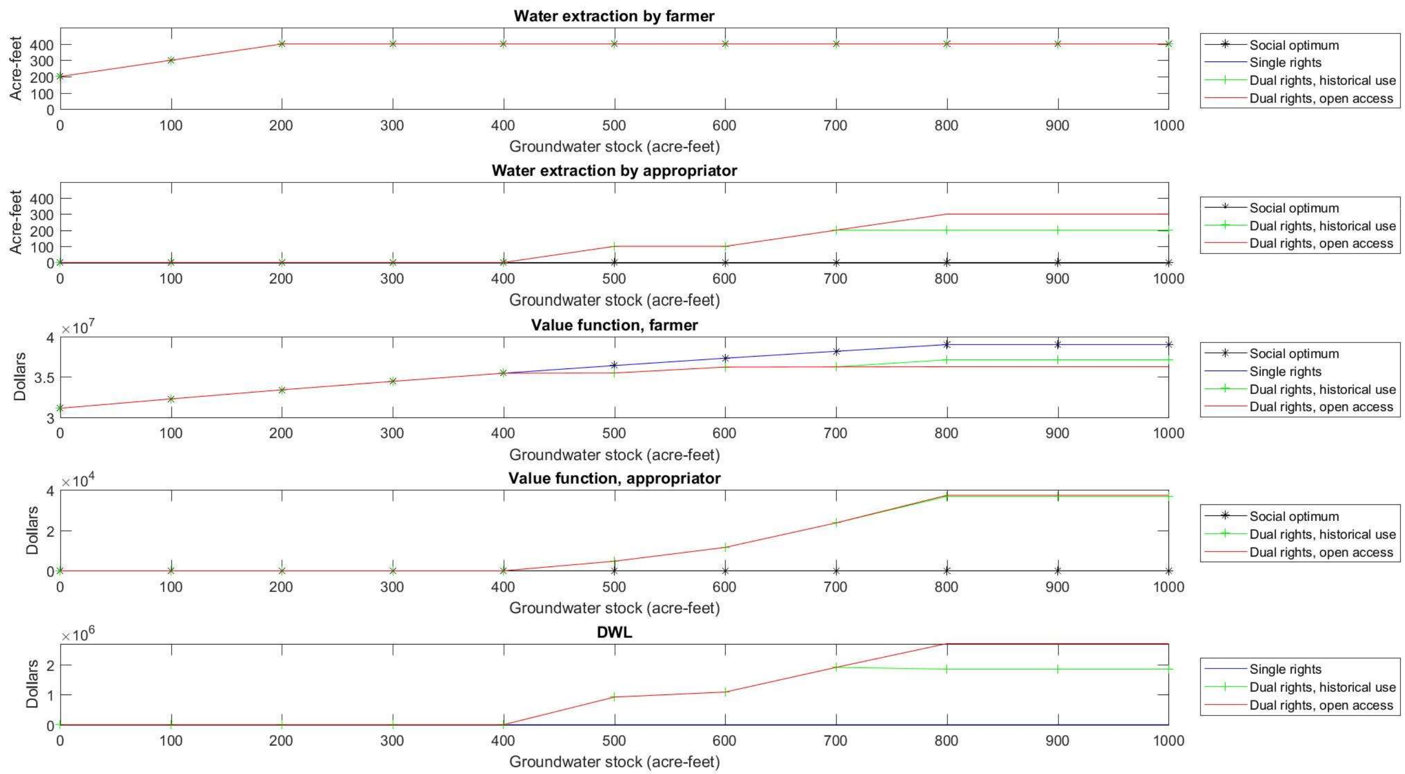


Figure A6: Share of water in crop production is 50% of baseline

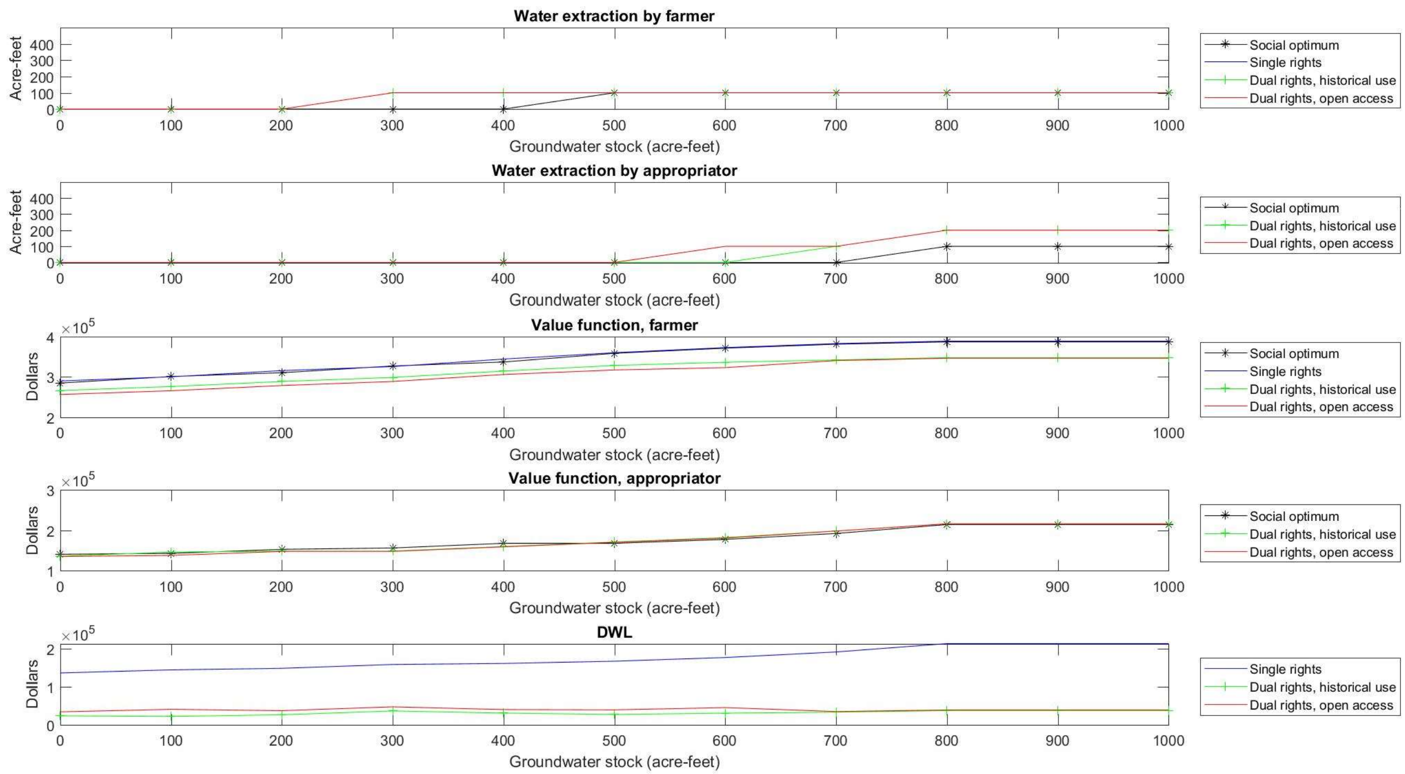


Figure A7: Technology of crop production is 105% of baseline

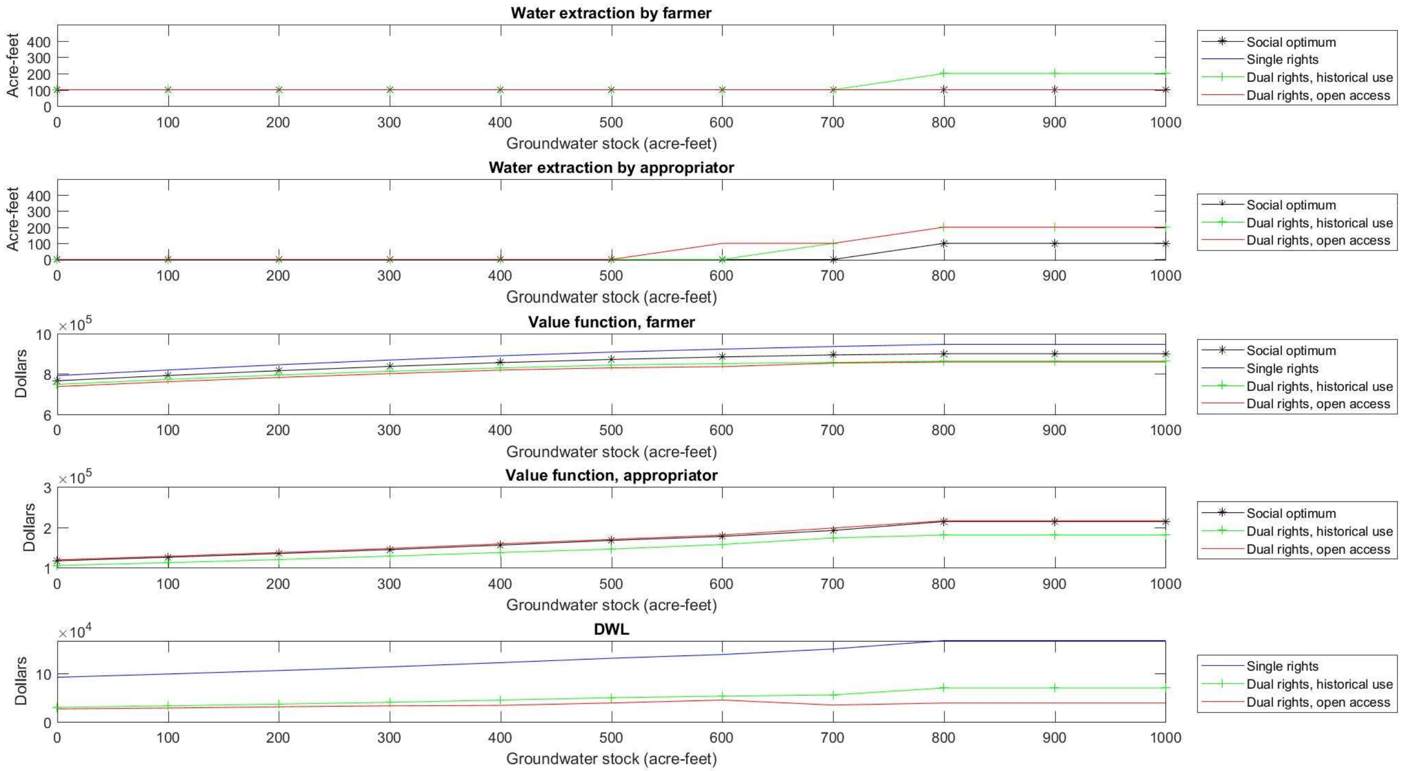


Figure A8: Technology of crop production is 50% of baseline

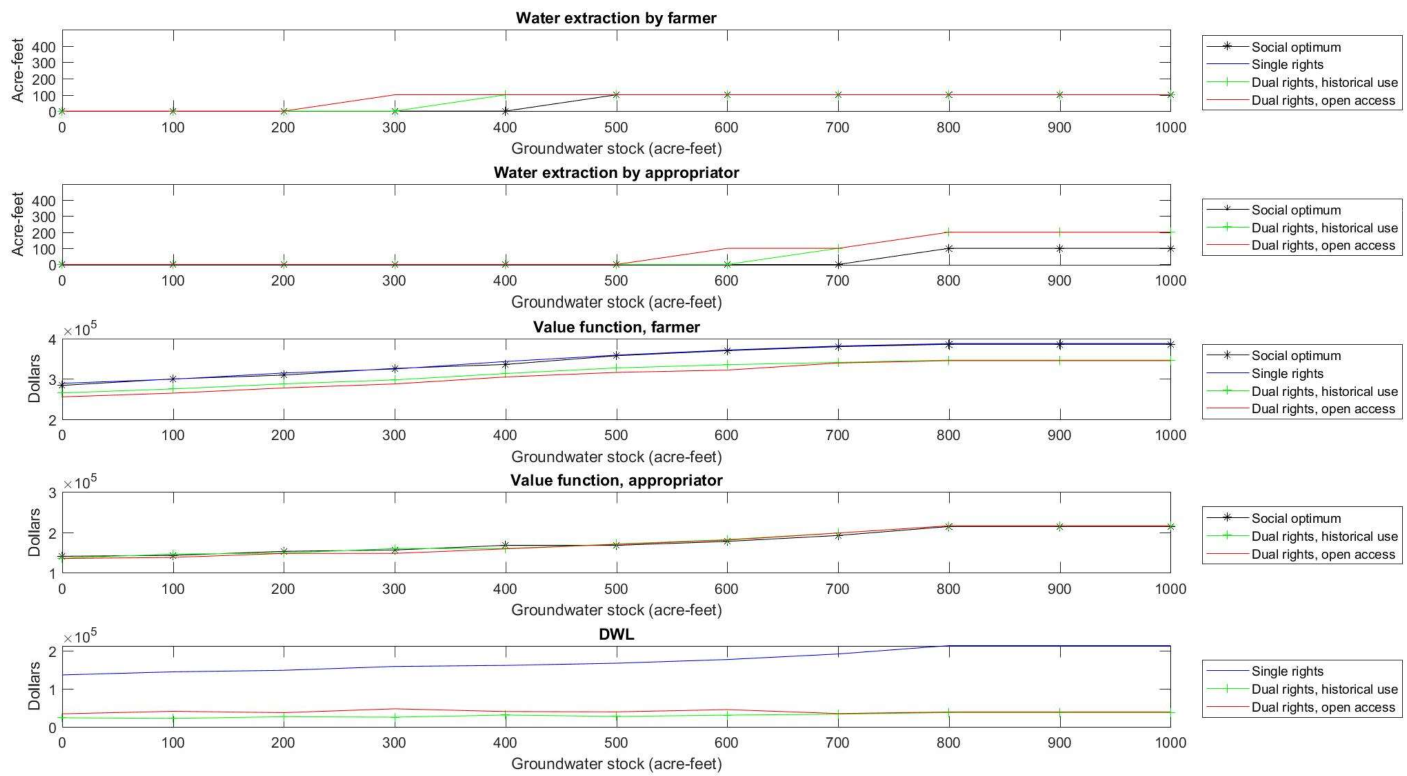


Figure A9: Price of electricity is 60% of baseline

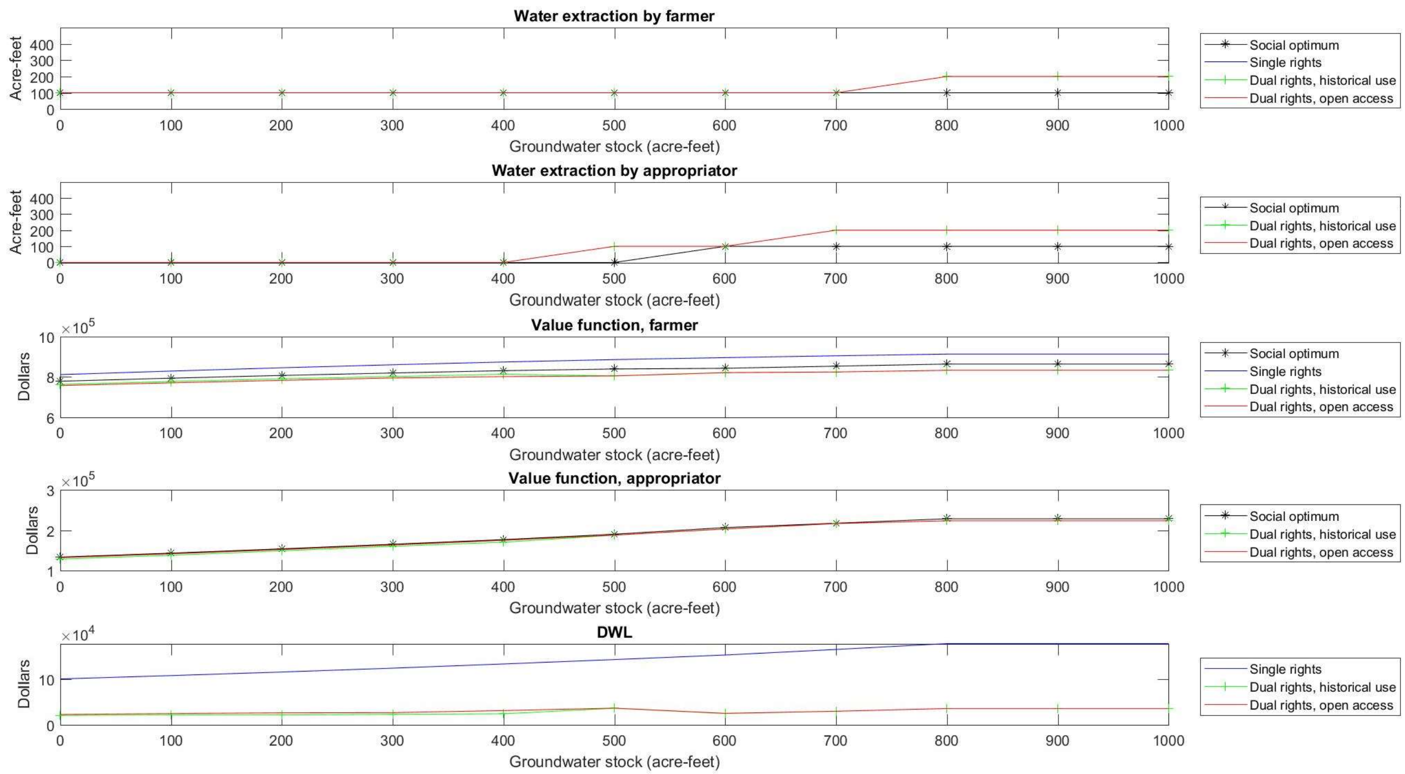


Figure A10: Drought

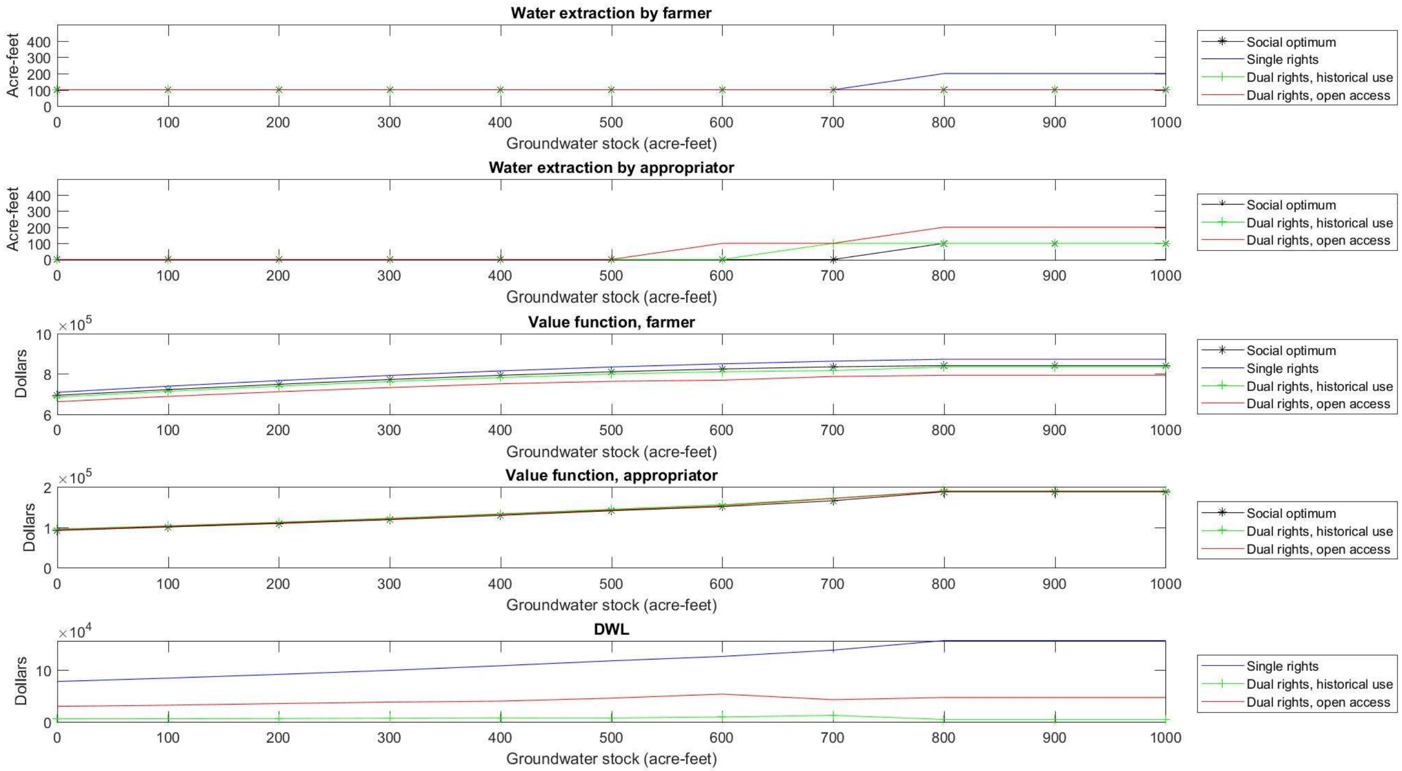


Figure A11: No drought

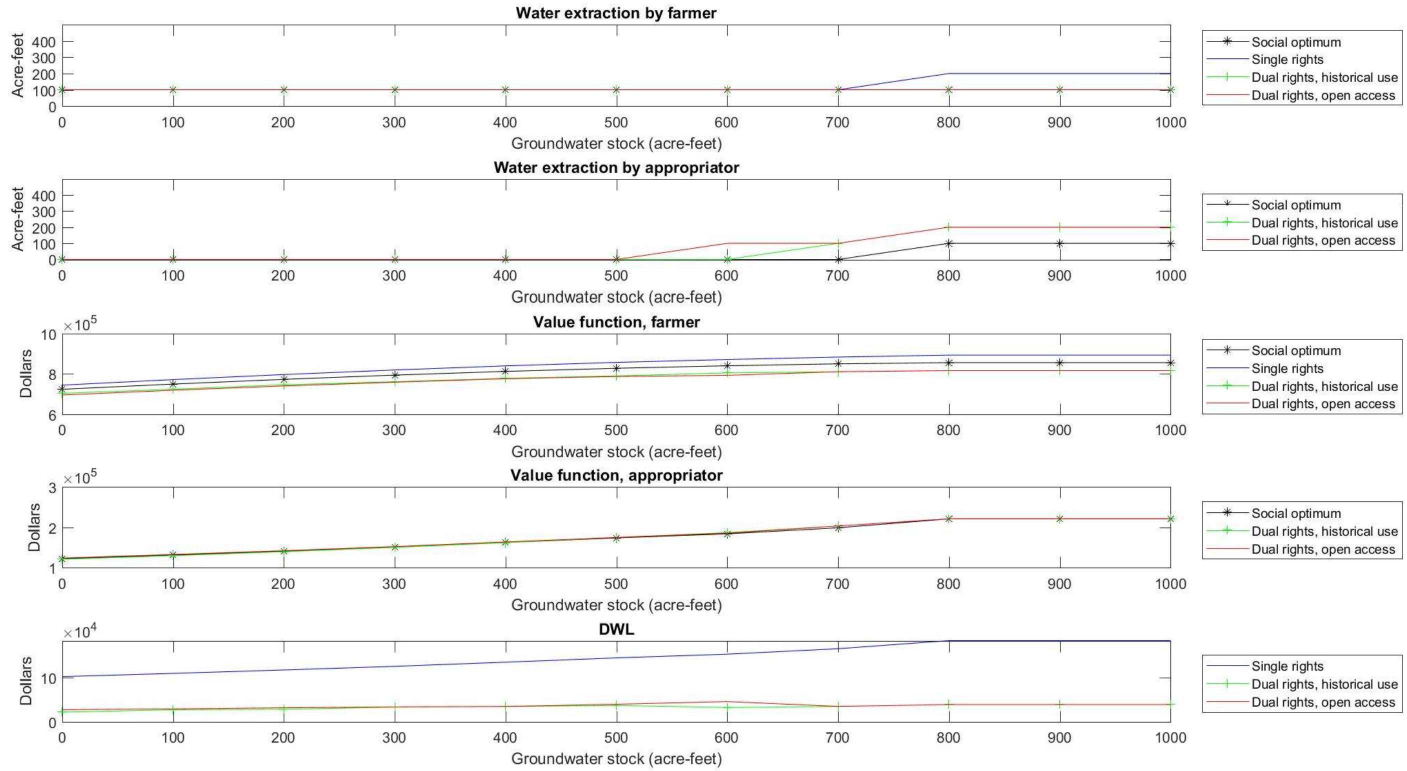


Figure A12: More extreme weather

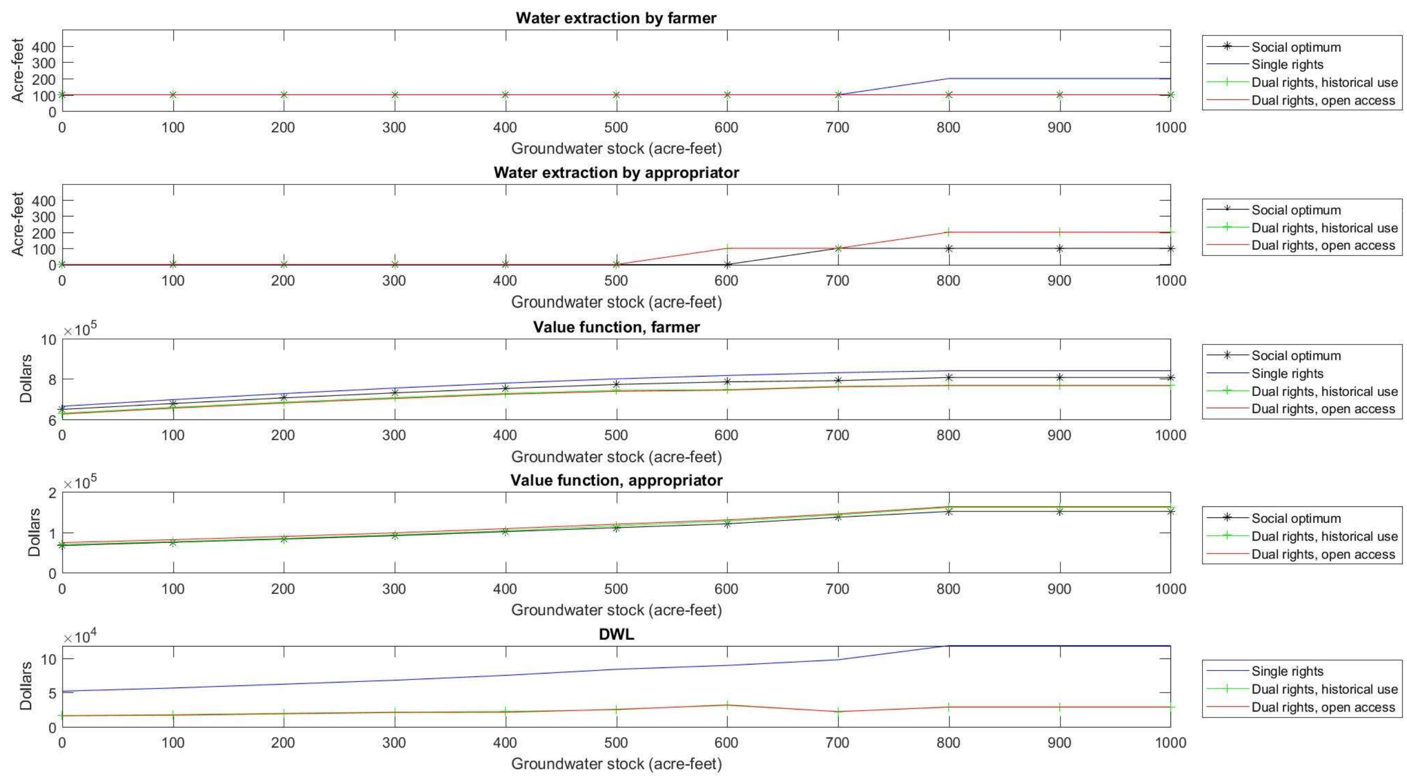


Figure A13: Extreme drought

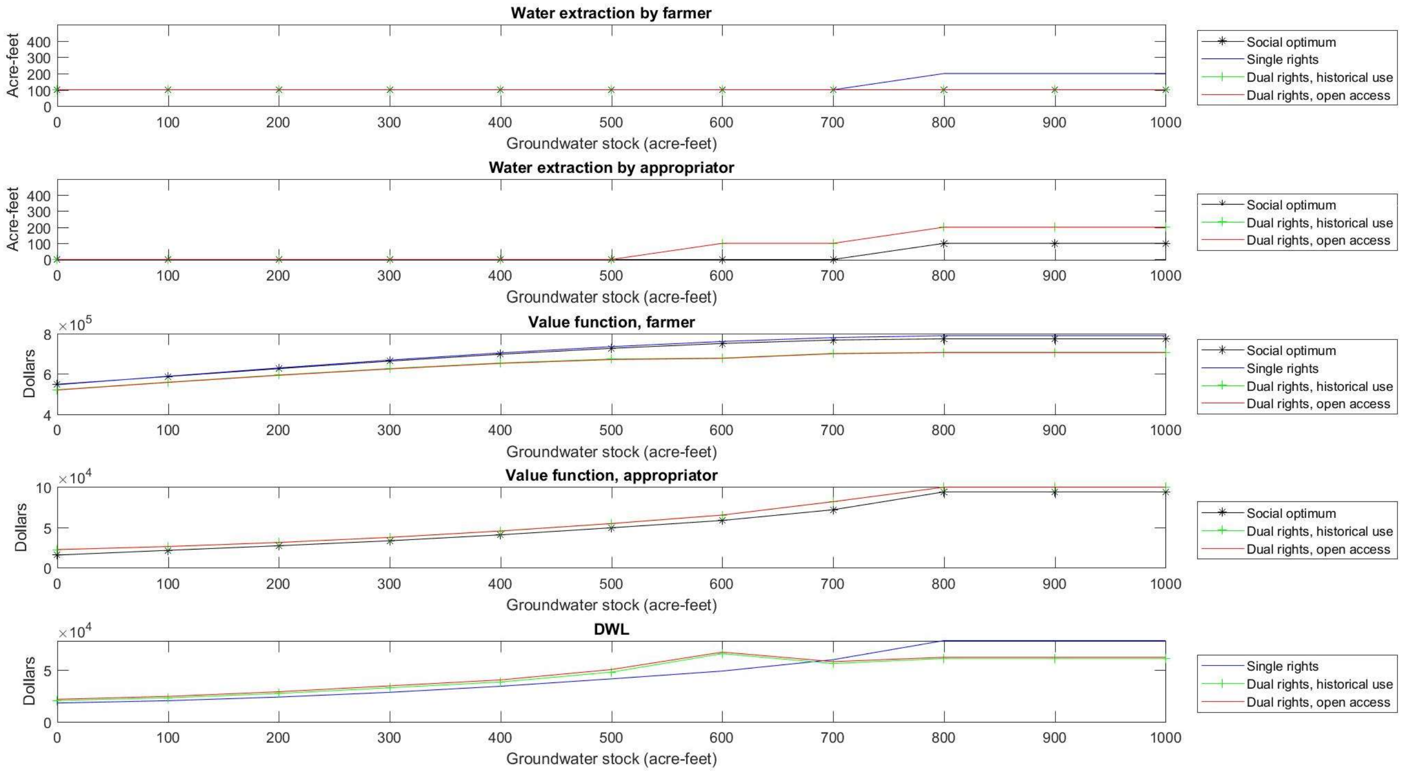


Figure A14: Share of stock reserved for appropriator higher (20 percent)

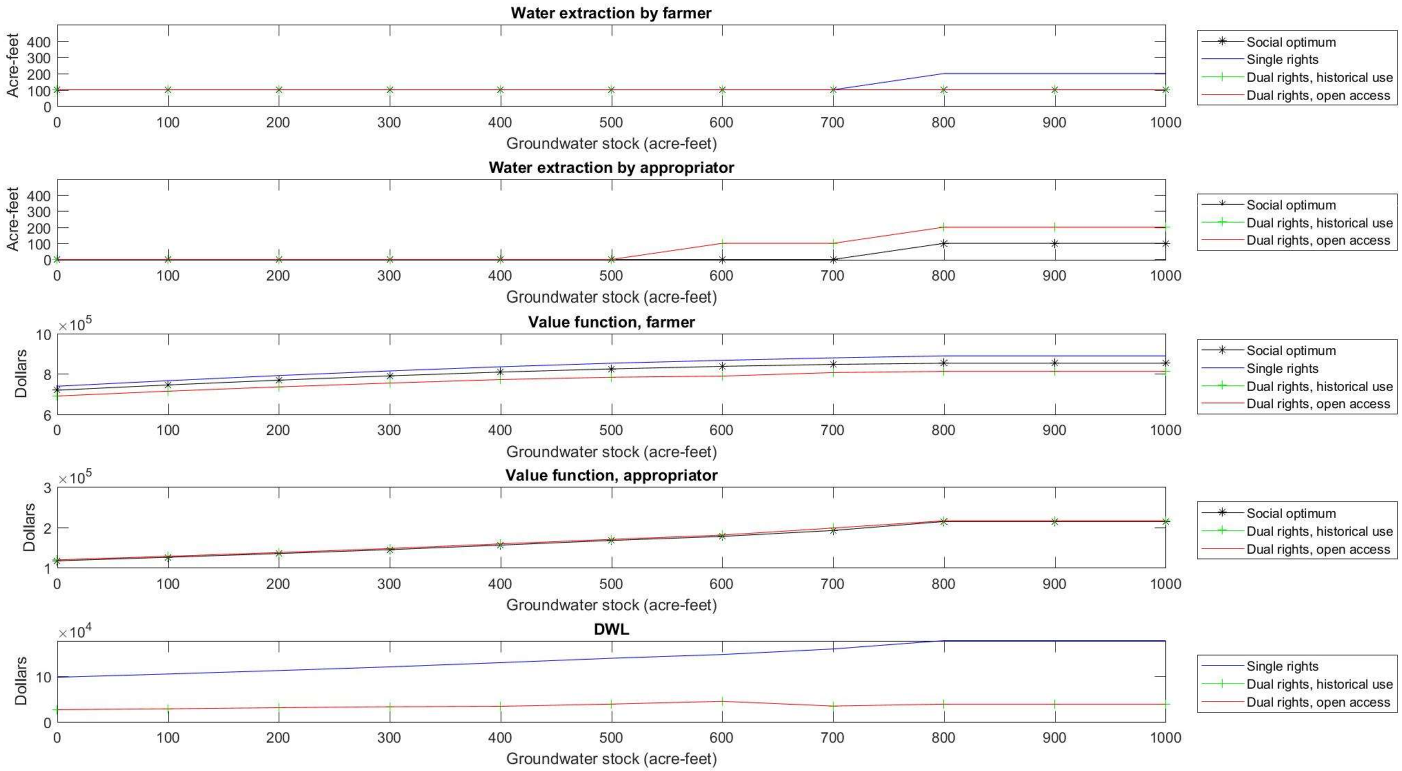


Figure A15: Share of stock reserved for appropriator lower (6 percent)

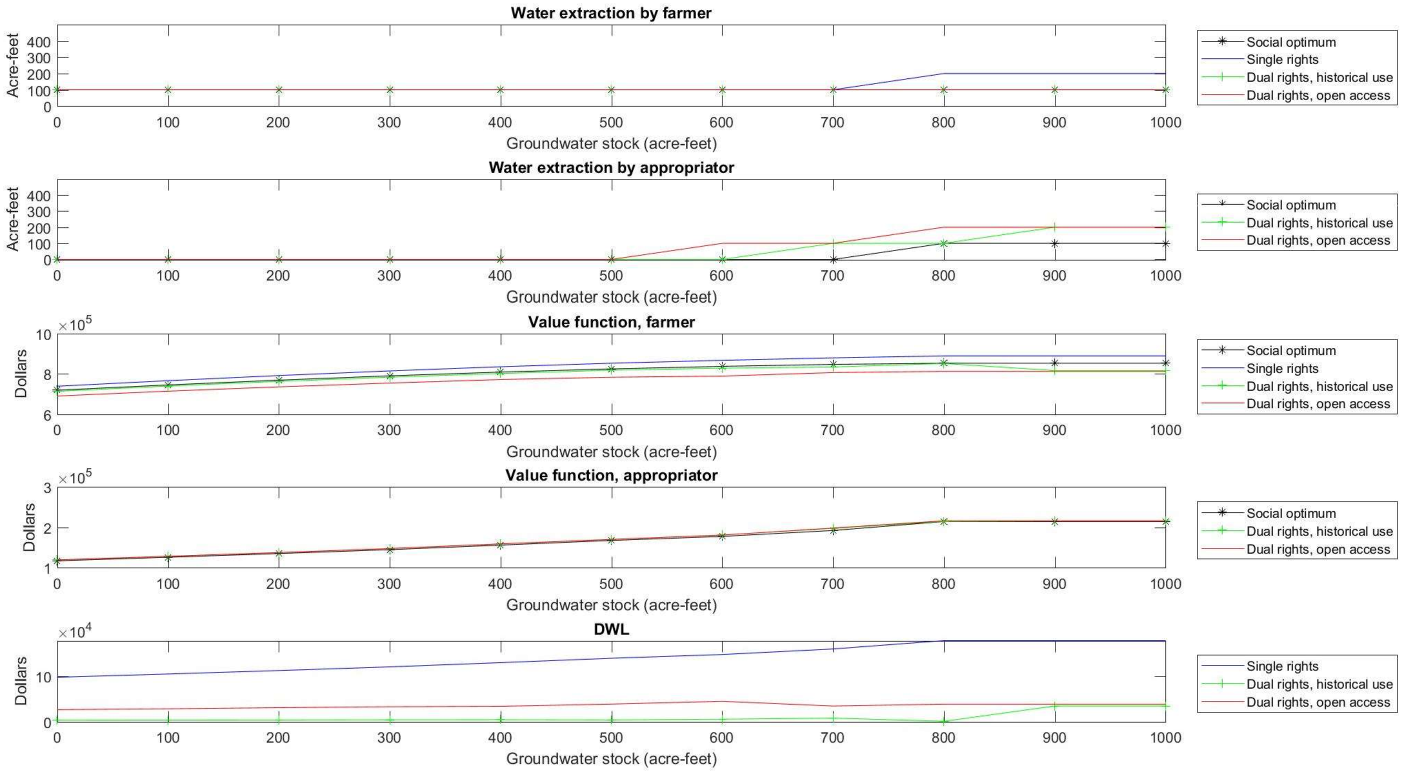


Figure A16: Length of historical extraction periods used for appropriator's property right higher (10 years)

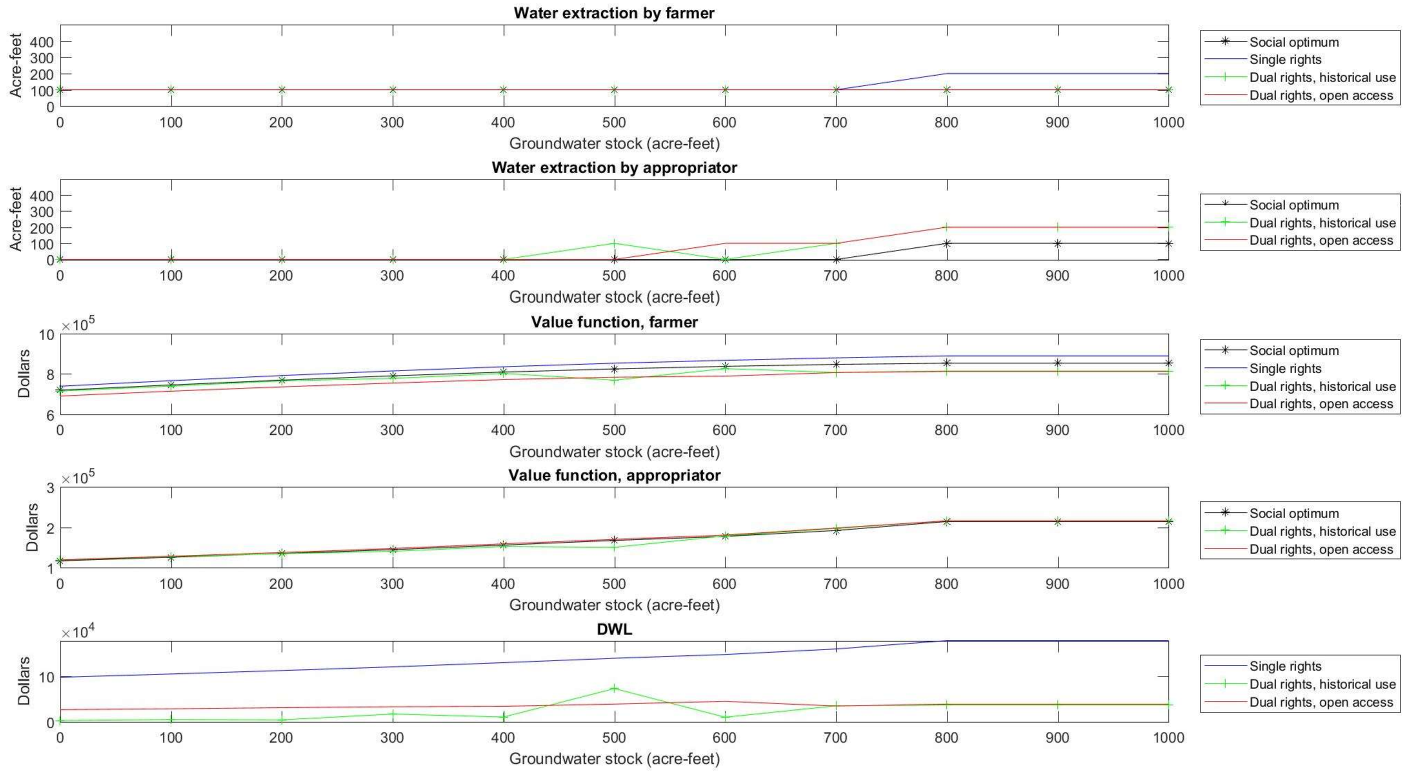
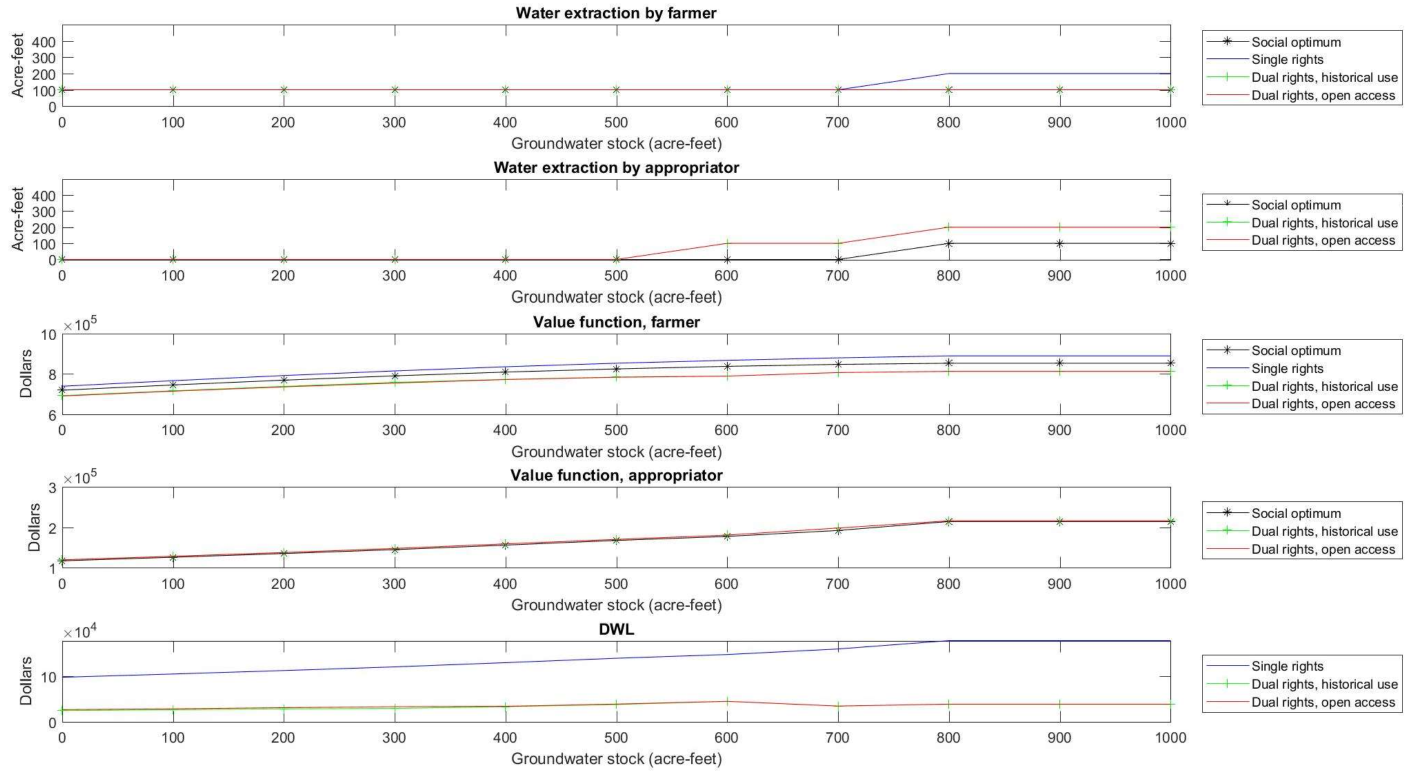


Figure A17: Length of historical extraction periods used for appropriator's property right lower (1 year)



Appendix B. Proofs

Proof of Proposition 1:

If $\lambda_{Wa} = 0$, then conditions [#1sf] and [#1sa] imply equation (23). □

Proof of Lemma 1:

Suppose towards a contradiction that the cap binds in the steady-state at time *t*: $w_a(t) = W_a(t) + \sigma s(t) = W_a(t) + \sigma \overline{s}$. Then, from equation (15), $\dot{W}_a(t) = \frac{W_a(t) + \sigma s(t) - W_a(t)}{\tau} = \frac{\sigma s(t)}{\tau} = \frac{\sigma \overline{s}}{\tau} > 0$. Then the cap $W_a(t) + \sigma \overline{s}$ on appropriator water extraction is increasing over time. If appropriator water extraction is constant and fixed at $\overline{w}_a$, this means that even though the cap binds in the steady-state at time *t*, the cap will not bind in the next period. Thus the cap cannot bind in the steady-state as $t \to \infty$. Thus, $\lambda_{wa} = 0$ in a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are constant. □

Proof of Proposition 2:

If $\lambda_{Wa} = 0$, then equation (32) reduces to equation (28), and equation (33) reduces to equation (29). Then the conditions (30)-(33) for historical use dual rights become the same as the conditions (26)-(29) for open access dual rights. □

***Proof of Lemma 2*:**

Taking the derivative of the solution for the groundwater stock trajectory $s(t)$ under historical use dual rights and setting it equal to 0 yields the condition:

$$\dddot{p}_w(t) = r\ddot{p}_w(t) + rB + \frac{B}{\tau} + \frac{K_f^d gr}{2rc\tau + K_f^d g\tau} B, \tag{37}$$

where:

$$B = -\frac{r + \frac{1}{\tau}}{\tau^2} \lambda_{Wa}. \tag{38}$$

Taking the derivative of the solution for the farmer groundwater extraction trajectory $w_f(t)$ under historical use dual rights and setting it equal to 0 yields the condition:

$$\dddot{p}_w(t) = r\ddot{p}_w(t) + rB + \frac{B}{\tau}. \tag{39}$$

Since both equations (37) and (38) must hold in a steady-state in which farmer water extraction, appropriator water extraction, and groundwater stock are all constant under historical use dual rights, this means that:

$$\frac{K_f^d gr}{2rc\tau + K_f^d g\tau} B = 0. \tag{40}$$

Equation (40) is only satisfied if either (i) the multiplier λ_{Wa} on the equation of motion for historical use $W_a(t)$ must be zero; (ii) the interval τ over which the moving average of the appropriator's prior pumping is calculated to determine historical use must be infinite, (iii) there are no stock effects ($g = 0$), or (iv) there is no discounting of the future ($r = 0$). □

***Proof of Proposition 3*:**

When there are no stock effects ($g = 0$), equations (27) and (29) reduce to:

$$w_f^{OA} = \frac{rK_f^{\kappa} p_c^{OA}(t) - K_f^{\kappa} \dot{p}_c^{OA}(t)}{2rc}$$

$$w_a^{OA} = \frac{rp_w^{OA}(t) - \dot{p}_w^{OA}(t)}{2rc}$$

Similarly, when there are no stock effects ($g = 0$), equations (35) and (36) become:

$$w_f^{SP} = \frac{rK_f^{\kappa} p_c^{OA}(t) - K_f^{\kappa} \dot{p}_c^{OA}(t)}{2rc}$$

$$w_a^{SP} = \frac{rp_w^{OA}(t) - \dot{p}_w^{OA}(t)}{2rc}$$

Thus, steady-state extraction under the open access dual rights system equals steady-state extraction under the social optimum for both players.

However, when there are no stock effects ($g = 0$), equations (31), and (33) reduce to:

$$w_f^{HU} = \frac{rK_f^{\kappa} p_c^{HU}(t) - K_f^{\kappa} \dot{p}_c^{HU}(t)}{2rc}$$

$$w_a^{HU} = \frac{rp_w^{HU}(t) - \dot{p}_w^{HU}(t) - \lambda_{Wa}/\tau^2}{2rc}$$

Thus, steady-state extraction for farming under historical use dual rights equals steady-state extraction for farming under the social optimum if there are no stock effects. If λ_{Wa}/τ^2 equals zero, then the appropriator extraction is also equal to that under the social optimum and open access. However, if λ_{Wa}/τ^2 is non-zero, the appropriator's extraction under historical use dual rights will differ. λ_{Wa}/τ^2 is non-zero if and only if the multiplier λ_{Wa} is non-zero and τ is finite. □

Proof of Propostion 4:

From equations (29), (33), and (36), we obtain:

$$w_a^{OA} - w_a^{SP}$$

$$= \left(\begin{array}{l} \left(K_d^f \left(rp_w(t) + \dfrac{2rc + gK_a^d}{2c} \left(p_c(t) K_f^\kappa + g(S-s) \right) K_f^d \right) \right) \\ - \left(\begin{array}{l} \dot{p}_w(t) + rg(S-s)K_a^d \\ + \left(2rc + gK_a^d\right) \left(2rK_a^d (S-s) + \dfrac{K_f^d}{2c} p_w(t) + \dfrac{K_f^d}{2c} g(S-s) K_a^d \right) \end{array} \right) \end{array} \right)$$

$$\cdot g\left(2rc + g(K_f^d + K_a^d)(2rc + gK_a^d\right)^{-1}$$

$$w_a^{HU} - w_a^{SP}$$

$$= \left(w_a^{OA} - w_a^{SP}\right) - \frac{\frac{\lambda_{Wa}}{\tau^2}}{2rc + gK_a^d} < \left(w_a^{OA} - w_a^{SP}\right)$$

Thus, if $w_a^{OA} - w_a^{SP} > 0$, then the appropriator (i) overextracts (relative to the social optimum) under open access dual rights, and (ii) extracts less under historical use dual rights than under open access dual rights. On the other hand, if $w_a^{OA} - w_a^{SP} < 0$, then the appropriator (i) underextracts (relative to the social optimum) under both open access dual rights and historical use dual rights, and (ii) underextracts more under historical use dual rights than under open access dual rights. Since $\dfrac{\partial(w_a^{OA} - w_a^{SP})}{\partial(p_c(t)K_f^a)} > 0$, a higher $p_c(t)K_f^a$ makes it more likely that $w_a^{OA} - w_a^{SP} > 0$, and vice versa. □