Abstract

In rapidly urbanizing semi-arid regions, increasing amounts of historically irrigated cropland lies permanently fallowed due to water court policies as agricultural water rights are voluntarily being sold to growing cities. This study develops an integrative framework for assessing the effects of population growth and land use change on agricultural production and evaluating viability of alternative management strategies, including alternative agricultural transfer methods, regional water ownership restrictions, and urban conservation. A partial equilibrium model of a spatially-diverse regional water rights market is built in application of the framework to an exemplary basin. The model represents agricultural producers as profit-maximizing suppliers and municipalities as cost-minimizing consumers of water rights. Results indicate that selling an agricultural water right today is worth up to two times more than 40 years of continued production. All alternative policies that sustain agricultural cropland and crop production decrease total agricultural profitability by diminishing water rights sales revenue, but in doing so, they also decrease municipal water acquisition costs. Defining good indicators and incorporating adequate spatial and temporal detail are critical to properly analyzing policy impacts. To best improve agricultural profit from production and sale of crops, short-term solutions include alternative agricultural transfer methods while long-term solutions incorporate urban conservation.

Introduction

Water from rivers throughout the western United States allows for the irrigation of lands that collectively are among the most productive agricultural systems in the world. However, maintaining agricultural production in these regions is increasingly challenging due to rises in demand for water associated with rapid population growth. Given the growing costs (social, environmental, and financial) and limited opportunities to develop new supplies, utilities have turned to purchasing agricultural water rights to meet new demands. The reallocation of water rights from agricultural to municipal uses often results in the permanent dry-up of agricultural lands (McMahon and Smith 2013, Payne et al 2014), which often has significant negative impacts on the rural, agricultural economies from which water is purchased (Howe and Goemans 2003, Pritchett et al 2008).

Concerns regarding the distributional impacts of permanent transfers, together with strong public sentiment for maintaining healthy rural communities, has created increased interest in the development of alternative means to meeting future demands (Colorado Water Conservation Board 2016, Thorvaldson et al 2010). This includes an increased reliance on conservation, as well as various temporary transfer methods that would leave agricultural water right
ownership intact, while providing cities with a secure water supply during periods of drought. Examples of the latter include rotational fallowing agreements (McMahon and Smith 2013) and option contracts (Michelsen and Young 1993). Despite public calls to increase the utilization of these alternatives, the majority of new municipal demands continue to be met by purchasing permanent water rights purchases at what is considered a ‘firm yield’, or the amount of water supply from the source that meets average demand from the city nearly 100% of the time (Zellmer 2008).

An enhanced understanding of the coupled natural and human responses, interactions, feedbacks, and thresholds in food and water systems is vital to comprehensively assessing the feasibility, advantages, and disadvantages of alternative institutional settings. Identifying strategies that allow for the more efficient use of existing supplies is crucial to enhancing the resiliency and reliability of regional water systems for agricultural production. However, both of these require developing an understanding of not only the potential benefits and costs of various water management strategies, but also the distribution of those benefits and costs.

Previous analysis frameworks have relied on aggregate optimization or global welfare optimization assuming that decision-makers can ‘turn all the knobs’ and have the sole objective of maximizing social welfare (Brown et al 2002, Harou et al 2009). However, these types of approaches fail to capture the full range of institutional constraints, the often conflicting objectives and the decision processes of specific segments of society (Britz et al 2013). Input-output modeling techniques have been used to estimate the negative ‘economic impacts’ of water rights transfers; however, these approaches require unrealistic ‘heroic’ assumptions and only provide insight into impacts on expenditures as opposed to profit or consumer surplus (Howe and Goemans 2003, McMahon and Smith 2013, Thorvaldson and Pritchett 2007). Recently, advances have been made in the use of fully-coupled hydro-economic modeling to evaluate water allocation institutions and resulting impacts on agriculture for theoretical water systems (Bauman et al 2015, Britz et al 2013, Zhao et al 2013). However, impacts and nuances of proposed policies, institutions, or governance systems across time and space cannot be broadly applicable without accurate parameterizations for specific cropping systems across regions. Previous studies neglected to incorporate these factors due to intensive data and modeling requirements.

The goal of this study is to develop an integrative framework for the assessment of the effects of population growth and land use change on agricultural production, municipal water acquisition costs, and water supply reliability in semi-arid regions. The framework aims to evaluate the viability and tradeoffs of alternative management strategies across time and space to analyze the extent of direct impacts on agricultural producers and municipal water providers, as well as to identify potential negative third-party impacts to rural economies that result from changes in agricultural production. To meet this goal, the objectives of this study are to (i) develop a mathematical characterization of water allocation in a semi-arid region, and (ii) assess the viability of agricultural production systems amongst other stakeholder interests across time and space under various policy changes. The assessment framework developed in this study leads to a better understanding of resources under stress, integrating physical, ecological, and socioeconomic feedbacks. Integrated modeling and optimization reconciles regional water resource sustainability, socioeconomic, and institutional criteria to explore optimal solutions across various objectives of multiple sectors across both time and space. The framework serves several benefits: (i) it reveals the feasibility of satisfying water demands under the prevailing governance systems, (ii) it exposes components of the hydrologic and governance systems that are key to achieving water allocation targets, and (iii) it determines cost-effective options to enhance the reliability of water resources while sustaining desired levels of agricultural production and livelihood of rural communities within spatially diverse semi-arid regions. No other study in peer-reviewed literature known to the authors has truly integrated agro-ecosystem, urban water demand, and agent-based modeling as is performed by this study.

**Methods**

An integrative assessment framework (figure 1) was developed to rigorously evaluate the effects of institutional change in combatting decline of agricultural land and production. The components of the framework for a given river basin include: (i) characterization of drivers of activity around water, water supply and demand regimes, and institutional agreements and other systems governing water allocation, (ii) development of a hydro-economic model that mathematically defines relationships between sectors and institutions, and (iii) system-level evaluation metrics for assessing the sustainability of the agricultural sector under policy and institutional alternatives.

The framework was applied to characterize the range of potential impacts associated with a variety of alternative management institutions currently being considered within the South Platte River Basin (SPRB) in Colorado, a basin encompassing one of the fastest growing areas in the US. The region provides an ideal test bed that is rapidly urbanizing and has significant agricultural production with intensifying competition for an already over-allocated water resource. Water in the region is allocated according to the prior appropriation doctrine where senior water right
holders, those that obtained water rights first in time, are prioritized for water delivery before junior water right holders.

Transfers of water rights to other owners incur transaction costs associated with physical conveyance and treatment systems in addition to water court fees and processes that enforce the prior appropriation doctrine. To avoid injury to senior water right holders, Colorado water courts will typically require agricultural land to be purchased alongside water rights and the cropland subsequently permanently fallowed with no agricultural activity on the land after a specified amount of time when urban water demands match the size of the purchased water right. Any water right not put to a beneficial use can be, according to law, taken away and available for others to use. Thus, deficit irrigating a crop, or reducing losses of water through more efficient irrigation technologies could result in loss of the water right, although methods are just now being considered in Colorado (and are part of the focus of this paper) to ease these restrictions and incentivize more efficient water use. An exception to this ‘buy and dry’ trend exists in the SPRB because of trans-basin water (i.e. water derived from another basin) which is treated differently than native water (i.e. water derived from precipitation, runoff, or recharge from within the basin). Imported water in the basin is primarily delivered by the Colorado Big Thompson (CBT) project from the Colorado River Basin west of the continental divide. Imported water can be used for any beneficial use within its service area and shares can be traded with no water court fees.

Since the 1970s, municipal and industrial (M&I) users of water have been purchasing water rights at a rapid rate and primarily from the agricultural sector. Figure 2 illustrates increasing water rights transfer to M&I entities and associated trailing usage of those water rights for municipal purposes, showing a preference of municipalities to own water and lease back to farmers in years of plenty than to lease water
owned by farmers. Methodology in assigning municipal and agricultural ownership of water rights\(^7\) in the figure is discussed in supplementary appendix A available at stacks.iop.org/ERL/12/085005/mmedia. The most rapidly growing populations primarily reside in municipalities close to the Rocky Mountains while agriculture production takes place farther east. To explore effects of spatial patterns in urban growth, the SPRB region was split into five subregions labeled North, North Central, Central, South Metro, and East as depicted in figure 2. The CBT project serves only the North, North Central, and East subregions. Supplementary appendix B contains further details about land use, cropping systems, and other information for the SPRB.

Hydro-economic modeling in this study builds primarily on developments with spatially-distributed partial equilibrium modeling with transactions costs (Bauman et al 2015, Britz et al 2013). The model integrates municipal and agricultural decision-making within a partial equilibrium model formulated as Multiple Optimization Problems with Equilibrium Constraints (MOPEC) characterizing a water rights market. Within the market, municipalities minimize cost to acquire a secure supply through purchase of water rights, and agricultural producers maximize profit from crop production and sale of water rights to municipalities. Supplementary appendix C further discusses the partial equilibrium model, its mathematical formulation and numerical solution procedure.

Characterization of supply and demand for the SPRB relies on extensive data collected by the State of Colorado Division of Water Resources. In particular, surface water supply for specific uses in the SPRB was estimated as historical annual average surface water diversions. Demand for water is characterized separately for profit-maximizing agricultural producers and cost-minimizing municipalities. Crop production curves presented in this study have two factors (acreage and irrigation volume) fitted to output of the DayCent agro-ecosystem model having constant elasticity of substitution (Solow 1956). A unique crop production function was estimated for each unique combination of cropping system, soil, county, and climate in the basin (supplementary figures D.2–D.6). Municipalities, driven by population growth, purchase water as land development occurs. Future land development is estimated by an autoregressive statistical model, and municipal raw water purchase requirements informed the amount of water required to be purchased for each new parcel of developed land. Definition, characterization, and quantification of water supplies and demands in agricultural and municipal sectors are further discussed in appendix D.

System-level sustainability indicators were defined to assess the advantages and disadvantages of proposed management practices, policies, institutions, and governance systems on the viability of agricultural production. These indicators can be summarized in three classes: cost of water to municipalities, agricultural profit, and reliability of water supply. Reliability refers to the probability of a water supply (i.e. the amount that can be diverted from the river according to water rights) being greater than or equal to a water demand (i.e. irrigation water to meet consumptive use of crops) in any given year, and measures how likely suboptimal conditions of water supply will exist for agricultural producers (Howe et al 1994). Selection and mathematical characterization of sustainability indicators are provided in supplementary appendix E. Sustainability indicators were quantified and compared for the following alternative policies:

A. Baseline: Buy and dry (B&D) governs water rights transactions and CBT municipal ownership is capped at 80%.

B. B&D 0%: Buy and dry requirements are completely relaxed (land does not have to be sold with water right).

C. B&D 50%: Only 50% of land needs to be sold with the water right.

D. No M&I cap: Removed cap of municipal ownership from CBT water.

E. M&I cap 80%: Capped municipal ownership in every pool at 80% (required raw water requirement (RWR) to be 88% of baseline).

F. RWR 90%: Reduce urban water consumption and consequently water purchase requirement to 90% of baseline.

G. RWR 80%: Reduce urban water consumption and consequently water purchase requirement to 80% of baseline.

These policy changes stem from proposed policies currently being considered within the SPRB that operate within the existing constraints of Colorado water law embodying alternative agricultural water transfer methods\(^8\), regional water rights management\(^9\), and urban conservation\(^10\). Policy A is baseline, because it represents the current institutional framework and policies regarding municipal ownership of water rights.

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\(^7\) Water rights data (Hydrobase), irrigated land area, and irrigated crop types are from the Colorado Division Support System through the Colorado Division of Water Resources and Colorado Water Conservation Board. http://cdss.state.co.us/Pages/CDSSHome.aspx.

\(^8\) Colorado Water Conservation Board, ‘Alternative Agricultural Water Transfer Methods Criteria and Guidelines for the Competitive Grant Program’ http://cwcb.state.co.us/loansgrants/alternative-agricultural-water-transfer-methods-grants/documents/altagrantprogramcriteriaandguidelines.pdf.

\(^9\) Municipal ownership of CBT water is restricted by their ownership from other water sources as described in this document www.northernwater.org/docs/About_Us/EventsAndPresentations/Policies/SUMMARIES_March18_2013.pdf.

\(^10\) Colorado Water Conservation Board (2016). Colorado’s Water Plan. www.colorado.gov/pacific/cowaterplan/plan.
CBT water (Squillace 2011). Policies B and C represents a move toward a more flexible institution allowing farmers to deficit irrigate crops instead of being required to sell and permanently fallow land in addition to the sale of water rights, but still incurs infrastructure and legal costs in transactions. Since 80% of water supplies could not serve all municipal needs, Policy E required the RWR to be lowered. The maximum RWR level equally applied to all cities was determined to be 88% of baseline levels. Lowered raw water requirement simulates less stringent municipal water purchase requirements for land developers granted they build with water-saving features. Policies F and G are similarly urban conservation policy scenarios. Further reasoning for and mathematical characterization of alternative management policies are discussed in supplementary appendix F.

The time period selected for analysis was from 1980 to 2050, solved each decade with a 40 year planning period, because of the benchmark data available from 1980 and population projections available until 2050 (Camp Dresser et al 2010). The water rights market model was solved each decade to show general trends within the 70 year period of analysis, and for comparative analysis of policy changes. Although the model, its parameterizations, time period, and sustainability indicators that are explored in the case study are specific to the SPRB, the integrated assessment framework is generally applicable. The study river basin also includes trans-basin water transfers (i.e. imported water) that would be suitable for the extension of the results to other regions.

Results and discussion

Results of the modeling framework were corroborated with historical cropland acreage, water rights ownership, and water rights prices between 1980 and 2010, and then projected to 2050 for analysis of the effects of continued population growth. The rate of decline generally followed trends of historical observations since 1980 with varying effects on agricultural production by cropping system and subregion (figure 3). Maintaining acreage in eastern Colorado is consistent with historical trends, likely because it is more expensive for cities to purchase water far downstream. Modeled alfalfa and corn showed opposite trends of decline compared to observed data likely due to unaccounted drought resilience of crops like alfalfa (and associated reduction of risk for the agricultural producer) or externalities that can drive alfalfa prices up such as livestock feed production. Even though the model incorporates constraints on the rate at which municipalities can purchase CBT water11, modeled municipal water rights purchases more heavily relied on CBT water than was historically observed because in reality cities face a higher cost of infrastructure development. Special attention was put on parameterization and calibration of spatial parameters in the model, particularly transactions costs to reproduce historical patterns of water prices and changes in cropland acreage by subregion. Further discussion on model limitations and potential future work can be found in appendix C, and discussion on model corroboration and calibration procedures are detailed in appendix D.

The baseline institution projected a loss of approximately 24% (175,000 acres) by 2030 and 68% (500,000 acres) by 2050 of total cropland (table 1), exceeding the estimated 33% loss in Colorado’s Water Plan (Colorado Water Conservation Board 2016) while undershooting other predictions of 400,000 acres lost by 2030 (Thorvaldson and Pritchett 2007). The net present value (NPV) of agricultural profit from production across the entire SPRB was about $6.1 billion, whereas sales from water rights

11 See footnote 8.
12 See footnote 7.
13 NPV was calculated over 40 years with a discount rate of 3%.
Average surface water reliability 48.0%  
Average price of water right in 2050 ($/AF)

Table 1. Simulated time-varying outputs for the baseline institution.

| Year | Acreage | Irrigation (ft) | Diversion (AF) | Production (tons) | Yield (tons/acre) | Prod. profit ($) |
|------|---------|----------------|---------------|-----------------|-----------------|------------------|
| 2010 | 736 000 | 1.09           | 2170 000      | 3380 000        | 4.9             | $221 000 000     |
| 2020 | 682 000 | 1.08           | 2000 000      | 3380 000        | 5.3             | $264 000 000     |
| 2030 | 562 000 | 1.07           | 1790 000      | 3170 000        | 6.1             | $282 000 000     |
| 2040 | 454 000 | 1.09           | 1590 000      | 2690 000        | 6.8             | $268 000 000     |
| 2050 | 237 000 | 1.04           | 1370 000      | 2210 000        | 10.0            | $202 000 000     |

Table 2. Policy impacts on simulated agricultural cropland and profits (between 2010 and 2050), water rights prices, municipal costs, and reliability of surface water delivery. + indicates the value improved and − indicates the value worsened. Some values are better when lower (e.g. cost), others are better when higher (e.g. profit). All dollar amounts are 2010 dollars.

| Output                                    | Baseline | Policy | B | C | D | E | F | G |
|-------------------------------------------|----------|--------|---|---|---|---|---|---|
| M&I cost for new population ($/person)    | $18 600  | −10%   | −2%| −0%| −12%|−16%|−30%|
| NPV of average profit from production ($) | $609 000 000 | +15% | +8%| −1%| +9% |+6% |+12%|
| Cropland in production in 2050 (acres)    | 221 000  | +292% | +143%| +3%| +76% |+54% |+96%|
| NPV of total average profit ($)           | $23 940 000 000 | −15% | −2%| +3%| −7% |−17%|−28%|
| Average price of water right in 2050 ($)  | $12 000  | −25% | −6%| +3%| −1% |−13%|−23%|
| Average surface water reliability         | 48.0%    | −36% | −29%| +0%| +2% |−2% |−2%|

*p Reliability is shown as absolute change instead of percent change since it is itself a percentage.

** Net present value of total agricultural profit assumes that cities purchase water in 2010 and lease it back to agricultural producers until 2050 when cities use the water as expected by growth.

purchases totaled about $17.9 billion. Thus, out of the total NPV of $24 billion, a large portion (about 75%) came from sale of water rights, displaying a strong financial motivation to sell water rights. The average net present value of water14 to the agricultural producer was about $13,900 per AF, whereas the average price for native and CBT water was $10,400 per AF and $29,800 per AF, respectively. That is, for the agricultural producer that owns CBT water, it is more than two times more profitable to sell the water than to work for 40 years on the farm, and for the native water right holder, it is almost just as profitable to sell the water today as it is to work for 40 years (not accounting for the rise of water prices and potential future sale of water). Any policies such as those investigated by this study that attempt to support or sustain agricultural production will naturally decrease the current value of water rights, which is not financially beneficial for farmers wishing to sell water rights.

Due to the heterogeneity of crop productivity in the SPRB, total acreage more rapidly declined as time progressed because municipalities in the Central subregion were driven by the regional water rights market to purchase water from the North subregion where producers utilize more cropland per unit of water than any other subregion. This pattern is consistent with historical trends in regional cropland decline, and could not have been achieved without properly informing the model of irrigation amounts and cropland acreages for each subregion individually (figure 3(b)). Although total cropland in production continued to decline through the entire time period, annual profit from production climbed until it peaked in 2030, and then by 2050 dropped below original 2010 levels by about $20 million per year (−9%). This decoupled relationship of production profit from cropland acreage demonstrates the importance of adding spatial detail to subregion parameters and time-dependent detail such as historically observed growth patterns of crop yield and price due to technology improvements (supplementary tables D.4, D.5).

Each policy investigated in this study had both advantages and disadvantages (table 2). Relaxing buy and dry agreements according to Policies B and C significantly reduced reliability of surface water supply to agricultural producers from 48% to 12% and 19%, respectively (supplementary figure E.1). According to the crop production submodel, farmers chose to keep cropland in production even while owning less water. Thus, despite the increased risk of loss to crop and profit, farmers deficit irrigated when they would have preferred (i.e. ‘demanded’ according to the perspective of a water manager) more water to fully irrigate the crop. Reliability was insensitive to other policy changes that coupled land with water purchases. Policies B and C maintained agricultural profit from production and a large amount of cropland, including land that either converted to dryland or deficit irrigation practices, but still decreased total agricultural profit through lowered water rights prices. The policies caused a market-driven shift of purchases to the North subregion that has both lower productivity (marginal value) and lower transactions costs, driving down the price of water rights.

All policy changes except Policy D increased annual agricultural production profit 6%–15%, but net present value of profit including water rights sales

14 See footnote 13.
revenue decreased by 2%–28%. Policies F and G lowered the cost of water rights purchases for municipalities more extensively than other policies by conserving water in new developments. Because it required a large amount of urban conservation (RWR was 88% of baseline), capping municipal ownership of water in all subregions (Policy E) closely resembled effects of Policies F and G, but better maintained agricultural profit and value of water rights at a larger cost to municipalities (figure 4). All policies improved municipal costs for attaining water for new developments, especially policies with urban conservation (Policies E–F), although placing a cap on municipal water ownership (Policy E) did increase the cost of water relative to Policy F at a similar level of conservation. Some of the cost savings that Policy E would have attained with urban conservation, it lost by capping municipal ownership on all subregions at 80%. A regulation aimed at incentivizing certain behavior will perform worse for the system than the behavior itself, especially when spatially naive.

Most policies increased the total profit from production and the total number of acres in production above baseline policies, except for Policy D, where acreage drops below baseline slightly (figure 4). Removing buy and dry constraints (Policy B) enhanced agricultural profit from production when planning 10–30 years in advance, but since cities are still buying up water at the same rate, agricultural production and profit continued to decline. Water conservation of new urban developments (Policy G), however, improved agricultural production profit more when planning 30–40 years in advance. Eventually, urban water conservation also cannot completely sustain agricultural production, and the only methods would be to (i) support agricultural production in wet years while allowing cities to use water in dry years, (ii) pursue new sources of water, (iii) force cities to cap growth by water consumption and undertake reduction or reuse of water, or (iv) a combination of these. Short-term optimal solutions are not the same as long-term optimal solutions.

Effects of alternative water management policies on sustainability indicators vary considerably across subregions (figure 5). The North subregion generated the most profit from production and sale of crops, the East subregion had the most reliable supply of agricultural water and the highest cost of water rights purchases to municipalities, and the South Metro subregion had the highest price on water. Figure 5(b) visually represents average performance of each
scenario on a radar plot so that a fuller radar plot characterizes better (non-dominated) solutions. For example, the radar plot of Policy E is larger than Policy F, showing its dominance over Policy F using the indicators defined in this study. In reality, Policy E would likely receive much more political opposition than Policy F because it adds significant and invasive restrictions on ownership of water by municipalities. This trade-off highlights the importance of determining a reasonable variety of indicators to evaluate system performance that represent values and perspectives of as many stakeholders as possible, weighted by the size of their stake. The main obstacle to inclusion of indicators such as political viability of solutions includes the lack of a generalizable quantitative metric to compare across alternative solutions and scenarios, which is a topic for further investigation.

Conclusions

Permanent purchases of water under current policies also permanently dry up agricultural land. This study reveals that cropland in rapidly urbanizing water scarce regions will continue to decrease except under complete removal of buy and dry transfer agreements. However, total profit from continued agricultural production can continue to increase especially under more flexible water rights administration and urban conservation. This decoupled relationship between agricultural cropland and profit illustrates the importance of carefully selecting key indicators to properly assess alternative policy impacts.

Water rights and trans-basin water shares are property rights that have much more value than continuing in production such that selling a CBT water share is about two times more profitable than the profit gained from 40 years of production (discounted over time at a rate of 3%). Modeling results revealed that 75% of total agricultural profit came from sale of water rights, and that any policy to sustain agricultural cropland diminishes total agricultural profit because of lost sales revenue from water rights.

Heterogeneity of productivity over space and trends of yield improvements and crop prices over time explained both historical water rights price trends of yield improvements and crop prices over time at a rate of 3%). Modeling results revealed that 75% of total agricultural profit came from sale of water rights, and that any policy to sustain agricultural cropland diminishes total agricultural profit because of lost sales revenue from water rights.

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Policies that include alternative water transfer methods, restrictions on municipal ownership of water, and urban conservation are all shown to improve agricultural profit from production and sales of crops at a lower cost to municipalities, but at significant reduction to the price and underlying value of water rights. Relaxes buy and dry constraints (Policies B–C) kept the most acreage in production but hurt reliability and water rights prices, relaxing municipal ownership constraints (Policy D) was the only policy to improve total agricultural profit by shifting municipal purchases to CBT water, which is sold at a higher price than native water rights, and urban conservation (Policies E–G) most effectively reduced water acquisition costs for cities by reducing raw water purchase requirements for new developments. Restricting municipal ownership of water increased the cost of water to municipalities slightly, but maintained higher water rights prices and agricultural profitability.

Acknowledgments

This work was supported by the Agriculture and Food Research Initiative of the USDA National Institute of Food and Agriculture (NIFA) grant number #2012-67003-19904, and partially by National Science Foundation (NSF) IGERT Grant No. DGE-0966346: I-WATER: Integrated Water, Atmosphere, Ecosystem Education and Research Program at Colorado State University.

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