Irrigation Technology and Water Conservation: A Review of the Theory and Evidence

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Introduction

Climate change, population growth, and economic development increase competition for water and exacerbate water scarcity- and drought-related losses (IPCC 2014), resulting in the identification of water crises as the greatest global societal threat (WEF 2019). Farming currently accounts for roughly 70 percent of freshwater withdrawals worldwide (FAO 2019) and often constitutes the least productive (i.e., lowest value) use of freshwater resources (Damania et al. 2017). In this context, providing safe, stable, and profitable food production while making incremental water available to alternative uses, including the environment, requires efficiency improvements in agricultural water management (UN 2015).

Efficiency improvements in agricultural water management that are aimed at conserving water tend to be formulated in two ways: (1) by increasing *allocative efficiency* through water conservation policies (WCPs) (Pigou 1932; Hicks 1939; Kaldor 1939) and (2) by increasing *physical irrigation efficiency* through water conservation technologies (WCTs) (Israelsen 1950). Allocative efficiency is achieved when water is optimally distributed, which means that the marginal cost and marginal utility from resource use are equal. Most water allocation regimes worldwide fall into the following categories: common pool (groundwater), prior appropriation (the first person to withdraw water for a specific use is awarded the right), or administrative (at the discretion of the responsible water institution). These processes rarely

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allow for trade, and water is generally allocated inefficiently. Enhancing allocative efficiency through WCPs such as volumetric charges or market-based instruments (e.g., buybacks[1]) implies the redistribution of water resources among competing uses (e.g., from irrigation to the environment), thus changing the costs and benefits to users. Economic theory suggests that such asymmetries are desirable if those who benefit from the reallocation could hypothetically compensate those who are made worse off and still be better off themselves (Hicks 1939; Kaldor 1939). Historically, however, the ability of policymakers to solve complex water reallocation problems and achieve water conservation targets through WCPs has been constrained by resistance to policy reform and institutional barriers, and the resulting transaction costs (Garrick, Whitten, and Coggan 2013). Thus, a growing number of water scarce regions worldwide are promoting the use of WCTs to increase physical irrigation efficiency (Perry and Steduto 2017), which is commonly defined as the ratio of water consumption by the crops in a field to the water diverted from a water source (Pfeiffer and Lin 2014).

WCTs include sprinkler or drip irrigation systems, laser leveling of fields, piped delivery systems, canal lining, and other physical rehabilitation of irrigation and delivery systems. The conventional wisdom is that higher physical irrigation efficiency will reduce the demand for scarce water resources, thereby conserving water and enhancing both agricultural productivity and income on-site (i.e., for the irrigator adopting the technology) (Gleick, Christian-Smith, and Cooley 2011). This means that a Pareto efficient outcome (i.e., no one is left worse off and at least one user is left better off) is expected, thus removing reallocation conflicts between public and private interests and the related institutional and private transaction costs, which are often the main barriers to water policy reform (Rausser, Swinnen, and Zusman 2011; Gómez et al. 2017).

This article examines whether and how behavioral responses to WCTs by irrigators actually lead to water conservation in agricultural systems. First, we discuss water basin accounting definitions and key concepts to provide background on how Pareto efficiency improvements can be achieved through WCTs. We then present the results of a comprehensive review of the theoretical and empirical literature on WCTs that includes more than 230 studies. This review is aimed at: (1) identifying the socioeconomic preconditions for realizing Pareto efficiency improvements and (2) assessing whether the behavioral responses and impacts predicted in the theoretical literature hold in practice. This is followed by a discussion of the key lessons learned from experience with WCTs, which is based on an international workshop that brought together experts from academia, international organizations, and regional and national institutions at the European Union (EU) level to discuss the evidence presented in the previous sections.[2] The penultimate section reviews the literature on WCPs and discusses the policy and institutional changes necessary to achieve effective water conservation. We conclude that if the ultimate objective is water conservation, it is essential to adopt WCPs. In the final section, we summarize our findings, which challenge the conventional wisdom that adoption of WCTs generally results in water conservation.

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[1]Buybacks are "purchase tenders that compensate those irrigators that decide to relinquish (part of) their right to withdraw water" (Pérez-Blanco and Gutiérrez-Martín 2017).
[2]https://www.cmcc.it/article/water-management-from-panaceas-to-actual-solutions.

Water Basin Accounting: Definitions and Key Concepts

As noted earlier, the conventional wisdom has been that higher physical irrigation efficiency through WCTs will conserve water on-site without the need to reduce agricultural productivity and income, thus leading to a Pareto efficiency improvement (Gleick, Christian-Smith, and Cooley 2011). This section reviews key definitions and concepts in water basin accounting to identify the preconditions for this Pareto efficiency improvement to occur. First, we present and discuss the "classical" concept of irrigation efficiency, which underlies the common assumption that efficiency improvements lead to water conservation. Then, we present the accounting framework underlying the "fractions" approach recommended by the International Commission on Irrigation and Drainage (Perry 2007) and use it to classify the potential dispositions of water use and their contribution to effective water conservation.

Limitations of the Classical Concept of Physical Irrigation Efficiency

The classical concept of physical irrigation efficiency measures performance as a dimensionless ratio—for example, "the ratio of water consumed by the crop to total water withdrawals" (Israelsen 1950). Analysts and policymakers often estimate the expected water conservation potential of an irrigation modernization project by simply "scaling-up" improvements in this ratio, for example, by multiplying the incremental change in the efficiency ratio by the area (e.g., in hectares) of the project (Lankford 2012). Perhaps not surprisingly, most papers on WCTs use field measurements to calculate these ratios. Indeed, in a review of the water conservation potential of drip irrigation, van der Kooij et al. (2013) found that, of 49 studies, 44 described experiments conducted at the field level, while only 5 went above the field level (e.g., examined impacts at the catchment or basin level). This focus on "local" accounting (i.e., at the field level) ignores important impacts that are increasingly relevant to broader concerns about water scarcity (Grafton et al. 2018). Most importantly, under the classical approach, the proportion of irrigation water *not* reaching the crop is classified as a loss—an "inefficiency" with no value, as in a heat engine or an electricity distribution system. However, in many cases, this "loss" will actually contribute to increased groundwater recharge or downstream discharge through return flows, which can create economic value elsewhere through increased water availability for other uses.

The limitations of the classical concept of irrigation efficiency were first noted by Hansen (1960) and later confirmed by the US Interagency Task Force (1979) on irrigation water use and management, which suggested a new approach to the "losses" or "inefficiencies" component that acknowledges its potential economic value. In a seminal paper, Willardson, Allen, and Frederiksen (1994) proposed the use of fractions to designate the disposition of water used for irrigation. This proposed shift from the classical approach to the fractions approach has two key implications for measuring irrigation efficiency. First, the fractions approach recognizes that all of the water withdrawn for any purpose (including the "losses") goes somewhere and ensures that the law of conservation of mass is respected (because the sum of the components at each stage is constant). Second, the term "efficiency" is value-laden: with *more efficient* intuitively translating to *better*, while a change in the fraction of water devoted to a specific component is a neutral statement of fact, just as financial accounts neutrally record sources and uses of funds (Seckler 1996; Perry 2007). The accounting
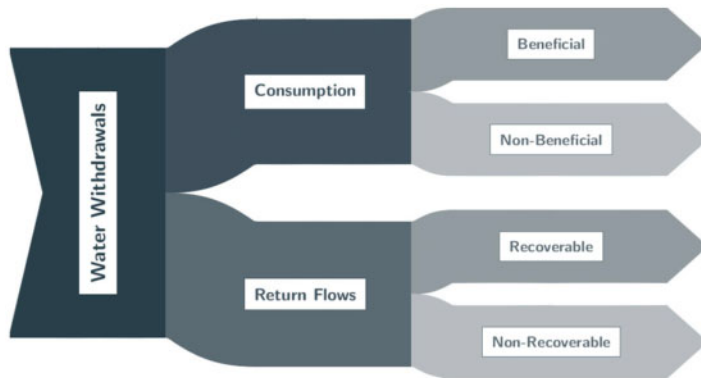
Figure 1   Water basin accounting of agricultural water withdrawals.
Source: The authors.

framework underlying the fractions approach, applied to water basin accounting of agricultural water withdrawals, is presented in figure 1, using the terminology proposed by the International Commission on Irrigation and Drainage (Perry 2007) to designate its components.

Water Withdrawals

Water withdrawals are defined as any water removed from surface or groundwater bodies for any use—for our purposes, irrigation. In the accounting framework in figure 1, all water withdrawals go to either:

1. The *consumed fraction*, which is water that is converted to vapor through plant transpiration and evaporation, and consists of:
   a. *Beneficial consumption* (i.e., water that is purposefully converted to water vapor, such as through crop transpiration) and
   b. *Nonbeneficial consumption* (i.e., water that is *not* purposefully converted to water vapor, such as through transpiration by weeds or evaporation from wet soil).
2. The *nonconsumed fraction* (i.e., the *return flows*), which consists of:
   a. *Recoverable return flows* (i.e., water reaching a usable aquifer or stream with downstream demand) and
   b. *Nonrecoverable return flows* (i.e., water flowing without benefit to a sink such as the sea, and therefore not usable).

This terminology is broadly applicable to any sector (e.g., agriculture, manufacturing industry) and at any scale (e.g., field, project, region, basin).

Water Conservation

In the accounting framework in figure 1, water is conserved when the amount of water depleted (i.e., through beneficial consumption, nonbeneficial consumption, and nonrecoverable flows) decreases, and thus water is released to alternative uses such as environmental uses. This means that WCTs can generate a genuine Pareto improvement in only two ways: (1) by reducing nonbeneficial consumption or (2) by reducing nonrecoverable return flow

(Clemmens, Allen, and Burt 2008). Either option allows water to be diverted to an alternative use without loss to the existing user.

Research has shown that for most field crops (e.g., grains, forage, sugar cane), yield is a "near-linear function" of crop water transpiration (i.e., beneficial consumption) (Steduto, Hsiao, and Fereres 2007, Perry et al. 2009). This suggests that for any additional water conservation to occur through WCTs there must be either a reduction in acreage, a shift toward less water-intensive crops, or an intentional reduction of crop water consumption through deficit irrigation, all of which reduce crop production and therefore preclude a Pareto improvement. This also means that when WCTs are introduced, any associated increase in yield will typically be directly and linearly correlated with an increase in water consumption.

Behavioral Responses to WCTs: Review of the Theoretical Literature

Once the opportunities to improve Pareto efficiency through WCTs have been identified, it is necessary to identify the preconditions for these opportunities to be realized. Beyond the hydrological processes occurring at the field, farm, and basin levels, the ability of WCTs to achieve water conservation at the basin scale depends on farmers' individual responses to increased physical irrigation efficiency and the institutional environment in which they operate.

Irrigators in agroecological systems can be regarded as rational agents who "seek to maximize their utility with respect to single or multiple attributes (e.g., profit, risk aversion), subject to a set of constraints (e.g., water availability)" (Graveline 2016). To this end, agents must make decisions concerning crop selection, land management, water application rates, and investments in capital stock such as WCTs. These agents do not have any specific preferences concerning these variables; they are only concerned about their effect on utility.

The literature on behavioral responses to WCTs typically assumes utility to be a function of profit (i.e., they use a single-attribute utility function) (Graveline 2016). WCTs have a positive impact on revenues mostly through increased beneficial consumption (e.g., acreage expansion) and the associated increases in production, which sometimes include higher value crops. Following the adoption of WCTs, some costs may increase (e.g., energy demand, capital investment, interest), while others decrease (e.g., labor, chemical input rates). The decision to invest in WCTs will also be affected by subsidies, which are typically used to encourage the adoption of WCTs by increasing expected profit (Grafton et al. 2018).

These impacts of WCTs on revenues and costs have two implications. First, because the incremental costs from WCT adoption may offset the incremental revenues, profit maximization is not necessarily associated with the highest possible physical irrigation efficiency. Indeed, profit maximization may be achieved at medium or low irrigation efficiency levels associated with low operational costs. Second, farmers who adopt WCTs rarely do so to conserve water; rather, they adopt WCTs because of their profitability (a proxy variable for utility). Thus, to determine the water conservation potential of WCTs, we must understand how increased physical irrigation efficiency affects the structure of costs and revenues (i.e., profit), as well as any other utility-relevant attribute, at the margin. Several theoretical

papers have examined various aspects of farmers' behavioral responses to WCTs; we review this literature in the remainder of this section.

Impacts on Water Application and Withdrawals

Early studies focused on how WCTs affect water application decisions at the farm level, and the impact of these decisions on irrigators' production and cost functions. Water application refers to the fraction of water withdrawals that is effectively delivered to the farm field for use by farmers, where the gap between water withdrawals and application indicates distribution losses (which may also constitute usable return flows). Since irrigators are the most relevant decision unit when assessing the adoption of WCTs, studies often focus on water application responses. For example, Caswell and Zilberman (1985, 1986) and Green et al. (1996) find that WCTs increase irrigators' costs, yield, and income, while generally decreasing water application and withdrawals. These authors also find that nonoptimal WCT adoption can reduce income (e.g., due to unforeseen incremental costs or less-than-expected revenues). In the case of drip irrigation, Dinar and Zilberman (1991) find that although increased physical irrigation efficiency reduces water application and withdrawals in the absence of drainage costs, in cases where drainage costs are significant, higher irrigation efficiency increases yields and intensifies water application, withdrawals, and related costs. Similarly, Peterson and Ding (2005) show that increased irrigation efficiency has an ambiguous effect on withdrawals that depends on production relationships.

The studies just discussed provide insights into the water conservation potential of WCTs only if *all* return flows are nonrecoverable (i.e., reducing withdrawals means water is conserved, regardless of the fraction of water consumed). However, these studies are not able to assess the impact of WCTs on water conservation when part or all of return flows are recoverable, which is the case for most river basins worldwide. For example, Peterson and Ding (2005) assess the performance of WCTs in the deep Ogallala Aquifer (United States), where water conservation can be assumed to equate to changes in farms' withdrawals "because the recoverable return flow to the aquifer is minimal and very slow." They find an ambiguous, although generally negative, impact of WCTs on withdrawals, while water consumption by crops consistently increases. If return flows are negligible, this means that farmers are increasing consumption at the expense of uneconomic nonrecoverable return flows, which leads to an improvement in Pareto efficiency; however, where return flows are partially or fully recoverable for other uses, increasing consumption will reduce water availability for these uses.

Impacts on Water Consumption

To investigate the impact of WCTs on water conservation when return flows are recoverable, we need to focus on changes in water consumption. Huffaker and Whittlesey (2003), Huffaker (2008), and Huffaker et al. (1998) examine the water use response to WCTs of a representative irrigator and find that when WCTs decrease the marginal biomass water productivity (i.e., yield per m^3 of water),[3] the profit maximization objective constrains the

[3]Note that here, biomass water productivity is measured in terms of applied water, since water application, rather than consumption, is the relevant variable for the farmer. Water licenses in the United States and

irrigator to reduce water withdrawals and consumption. However, for cases in which the WCT is subsidized (which is often the case in the United States), the impact on water consumption is ambiguous. In contrast, when WCTs instead increase the marginal biomass water productivity, the irrigator will always increase water consumption.

Similarly, Pfeiffer and Lin (2014) show that, provided that water demand is sufficiently elastic and WCTs result in lower marginal costs and higher revenue, higher irrigation efficiency will increase withdrawals and consumption by farms. Berbel and Mateos (2014) draw similar conclusions, but also note that water demand becomes increasingly inelastic as irrigation efficiency increases, thus progressively reducing the impact of WCTs on withdrawals and consumption. Gómez and Pérez-Blanco (2014) argue that the impact of WCTs on the decision about how much water to apply will depend on the balance between how sensitive water application costs are to increased irrigation efficiency (i.e., the efficiency elasticity of the water application cost) and how sensitive the marginal revenue of water consumption is to increased irrigation efficiency (i.e., the efficiency elasticity of the marginal revenue of water consumption) and conclude that WCTs in water-stressed basins are very likely to result in higher consumption by farms, which is exacerbated by subsidies.

Adamson and Loch (2014) and Loch and Adamson (2015) show that higher irrigation efficiency invariably increases water consumption and reduces return flows. Using a qualitative method for a general case that is based on economic, hydrological, and agronomic analyses, Whittlesey (2003) also finds that WCTs consistently result in higher water consumption by farms. Chakravorty and Umetsu (2003) and Umetsu and Chakravorty (1998) show that when WCTs replace traditional irrigation technologies in closed basins (i.e., basins in which water supply falls short of commitments to fulfill demand for part or all of the year), optimization over the entire basin leads to reduced water withdrawals and profit and increased water consumption at the basin level. Following the framework in Martin, Darrell, and James (1984), Contor and Taylor (2013) conclude that higher irrigation efficiency will make the irrigator able and willing to increase water consumption "at any nonzero marginal cost of water." Knapp (1992) finds that, under limited drainage conditions, optimal investment in basin-wide irrigation may require higher irrigation efficiency precisely to increase the fraction of water consumed by farms to limit water table build up (and the associated costs) and to ensure profit maximization. Analogously, the accumulation of agricultural pollutants in the water system's outflows can be addressed by using WCTs to "increase the consumed fraction of water at the expense of return flows" (Linneman et al. 2014). Finally, Carey and Zilberman (2002) note that, under conditions of uncertainty, "it is rational for farms to wait until the expected benefits of investment exceed the costs by a potentially large hurdle rate" before investing in WCTs, which again highlights that WCT adoption is driven by profitability. The uncertainty can be reduced through public subsidies, which, based on the flawed assumption that consumption will fall in response to increased physical irrigation efficiency, have been a major driver of the adoption of WCTs. Thus, our review of these studies suggests that a likely outcome of adopting WCTs is an increase in water consumption at the expense of reducing return flows.

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elsewhere are typically allotted and charged on the basis of water withdrawn for its application, independent of consumption.

Summary of Results

Overall, the results from theoretical studies of behavioral responses to WCTs suggest that increased physical irrigation efficiency is unlikely to conserve water under the generally prevailing conditions. On the contrary, WCTs will typically lead to increased water consumption by farms and reduced return flows, which, under prevalent recoverable return flow regimes, will reduce water availability for other uses. Our review of the theoretical literature reveals a dichotomy between classical irrigation efficiency (which aims to increase the ratio of water consumption to withdrawals) and basin-wide economic efficiency, which is illustrated by WCTs that increase local irrigation efficiency at the expense of reducing water availability in downstream areas—a negative externality that leads to a decline in both Pareto efficiency and equity. When relinquished uses have a higher economic value than new uses, the gains will be insufficient to offset the losses, causing a net economic loss (i.e., it is allocatively inefficient). Only when the value of the social benefits (i.e., the private benefit plus positive externalities) generated by a given WCT over its lifespan equals or exceeds the social costs (i.e., private costs plus negative externalities) will the WCT be allocatively efficient at a basin scale. Without sensible policy guidance and WCPs, this desirable outcome is unlikely (Ostrom 2007). But because it is usually assumed that there are no downstream impacts of increasing the consumed fraction of the water withdrawals, the necessary WCPs are rarely considered by policymakers.

Behavioral Responses to WCTs: Review of the Empirical Literature

This section reviews the empirical literature that assesses the effectiveness and economic performance of WCTs to determine whether the behavioral responses and impacts predicted in the theoretical literature hold empirically.

Criteria and Methodology for Literature Review

The papers included in our review of the empirical literature were selected based on the following criteria:

1. The paper assesses the impact of WCTs, including sprinkler or drip irrigation systems, laser leveling of fields, piped delivery systems, canal lining, and rehabilitation of irrigation and delivery systems.
2. The paper examines responses from *decision units* such as irrigators, representative irrigators, or a benevolent regulator (i.e., an agent that optimizes returns to the policy basin-wide). This excludes studies at the field scale.
3. The impacts reported include information on at least one of the following variables: the WCT adopters' agricultural net income, water withdrawals, water consumption, and water conservation in the relevant system.

Application of these criteria yielded 213 empirical papers for a total of 230 individual WCT case studies, of which 112 are ex ante studies and 116 are ex post studies.[4] As shown in figure 2, the case studies are mostly located in the United States (64), Spain (36), India (36), China (18), and Australia (8), where WCTs have received significant government subsidies (Perry and Steduto 2017).[5] While the design of these subsidy programs reflects the specific characteristics of the area in which they were implemented, all of them share a common feature: they claim to promote water conservation.

To assess the effectiveness and economic performance of WCTs, we examined the impacts of WCTs on four key variables: agricultural income (defined as revenue net of costs for WCT adopters); water withdrawals; water consumption; and water conservation.[6]

Impacts of WCTs on Agricultural Income

We find that the agricultural income of WCT adopters increases in 82.9 percent of the 199 case studies for which such data are available. In the remaining case studies, agricultural income either falls (4.5 percent), does not change significantly (3.5 percent), or the results are ambiguous (4 percent). In six of the nine cases where income falls, authors find that the presence of complementary WCPs (in particular water charges and quotas) or reduced water availability (due to drought/growing scarcity or increased upstream consumption) is a key variable in explaining this outcome. WCPs and supply shocks strengthen the water availability constraint and exclude the crop portfolio choices that deliver higher utility, which typically depresses income. In this context, WCTs offer farmers the possibility to increase local water consumption and mitigate income losses, albeit at the expense of reducing return flows and water availability for other uses (Ray Huffaker and Whittlesey 2003). In the other three case studies in which income falls, one performed the analysis during the outbreak of the Escherichia Coli bacteria in 2011 in Spain, which was the key reason for the income decline (Soto-García et al. 2013), and the other two assess the impact of hypothetical WCT adoption scenarios (e.g., assuming all farmers invest in drip irrigation), thus ignoring farmers' preferences and behavioral responses. Such predefined WCT adoption scenarios do not address some important questions concerning the adoption of WCTs, namely: why should farmers adopt WCTs and reduce water consumption if income then decreases (by up to 54.2 percent in one of the scenarios considered in van Oort et al. 2016)? Why should they comply with area or yield restrictions if they can increase income by expanding acreage and/or yield? What policy or policies can be used to realize these scenarios?

This is not to say that the voluntary adoption of WCTs cannot result in income losses. Water policy is often characterized by "unfavorable surprises" (Grant and Quiggin 2013)—negative and unforeseen contingencies that lead to negative impacts on utility and income following the voluntary adoption of technologies such as WCTs. Where possible, "surprised" irrigators will revert to the previous system to negate further losses. This is precisely what occurred in the seven case studies in which there was no significant change in agricultural

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[4]A detailed description of the case studies and the information gathered are available in the online supplementary materials.
[5]Macro-regional or national-scale studies are indicated in boxes in figure 2.
[6]See the online supplementary materials for summaries of the results and details concerning the database.
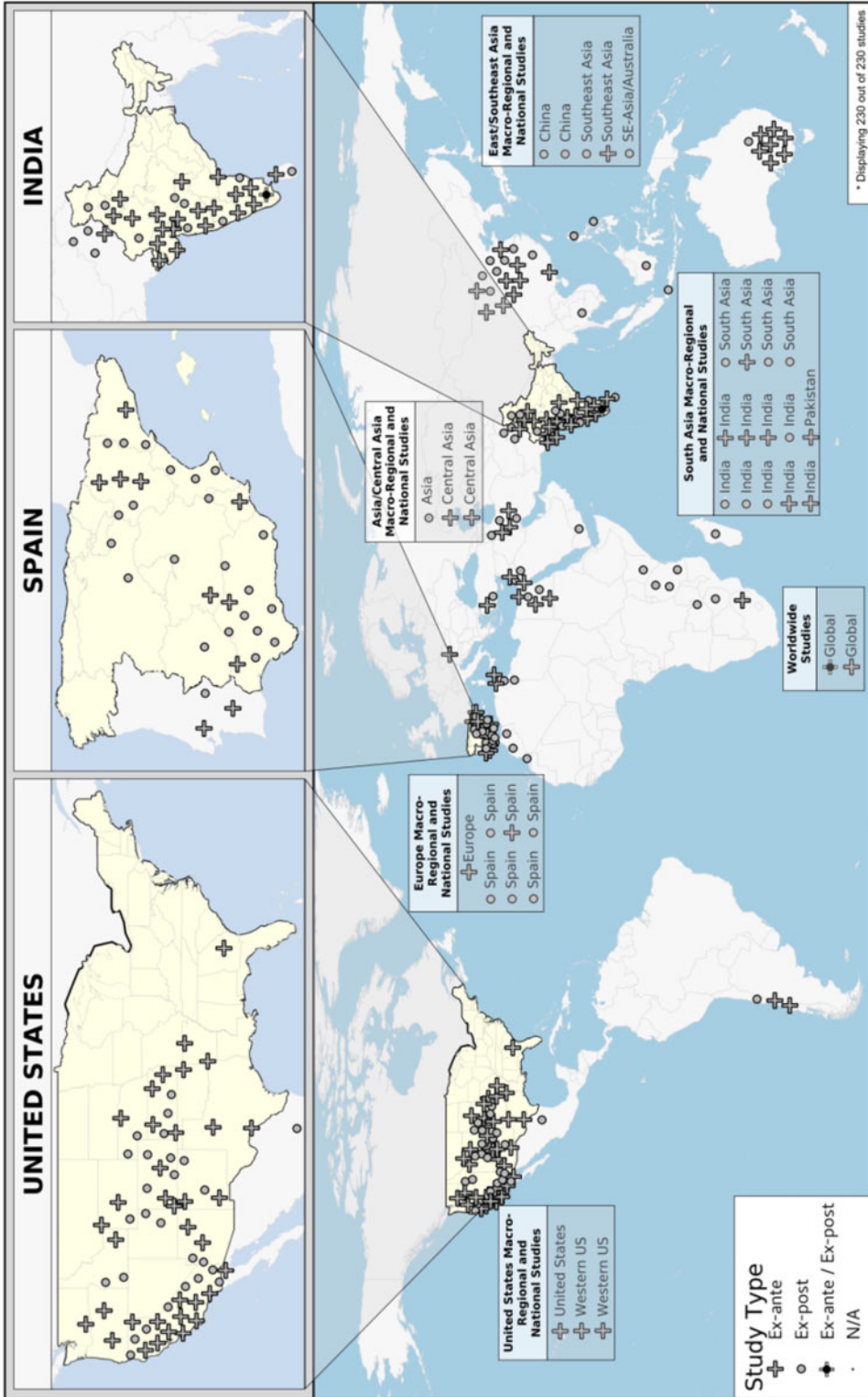
Figure 2 Location of selected case studies.

income: WCTs either did not meet farmers' needs or there was inadequate training, and WCTs remained unused—in some cases quickly deteriorating (Belder et al. 2007).

Impacts of WCTs on Water Withdrawals

Water withdrawals by WCT adopters decrease in 80.1 percent of the case studies for which this data are available (176), increase for 9.1 percent, and the results are ambiguous for the remaining 10.8 percent. As noted earlier, reduced water withdrawals by WCT adopters are the sufficient conditions to conserve water when *all* return flows are nonrecoverable. However, only 16 of the 230 case studies in our review are characterized by nonrecoverable return flow regimes. In the remaining 214 case studies (93 percent), we must focus on water consumption to assess the impacts of WCTs on water conservation.

Impacts of WCTs on Water Consumption

As reflected in figure 3, water consumption by WCT adopters increases in 83.2 percent of the case studies for which these data are available (161). In the remaining cases, consumption decreases (8.7 percent), there is no significant change (5 percent), or the results are ambiguous (3.1 percent). It is an issue of concern that the percentage of case studies reporting an increase in water consumption rises to 87.2 percent in closed basins. In a closed basin, higher consumption in one area "necessarily has [negative] third-party impacts, be it on other users, next generations or on the environment" (Molle, Mamanpoush, and Miranzadeh 2004). Indeed, higher consumption in closed basins generally leads to the growth of upstream systems through irrigation expansion and/or intensification, while reducing water availability and income in downstream regions, thus precluding the possibility of achieving a Pareto improvement. Achieving higher allocative efficiency is still possible, but would require the reallocation of water to higher value uses. This presents a challenge because agricultural WCTs generally increase water consumption in agriculture—usually the least economically productive water use—and are often used to expand the acreage of crops with low added value (Perry et al. 2009).

Of the fourteen case studies in which WCTs do reduce water consumption, four assess the conservation potential through hypothetical WCT adoption scenarios in which water resources are reallocated by a regulator, without exploring the additional interventions required to ensure this outcome. The remaining ten case studies in which water consumption decreases find that WCPs—such as quotas, land use restrictions, or charges—are the key driver in reducing water consumption. These studies suggest that in the absence of effective controls over actual consumption (i.e., not merely over the *right* to withdraw or apply water), farmers will increase water consumption to expand acreage and/or plant more profitable and water-intensive crops. Thus, without effective controls on water use, the likely impact of WCTs is that farmers will increase water consumption to increase agricultural income.

Impacts of WCTs on Water Conservation

To assess the impact of WCTs on water conservation, we examine changes in water availability for other uses, which are defined as changes in the (recoverable) groundwater recharge

Figure 3 Impact of WCTs on water consumption.

and surface water discharge at the outlet of the relevant agricultural system(s). Water available for such other uses decreases in 70.4 percent of the 152 case studies for which this information is available, and in 77.9 percent if we exclude nonrecoverable flow regimes in which incremental return flows have zero value (because they go to a sink from which they cannot be recovered). In the remaining case studies, water availability for other uses does not change significantly (12.5 percent), increases (11.2 percent) or the results are ambiguous (5.9 percent). As discussed earlier, water conservation is achieved when there is a decline in nonrecoverable flows, nonbeneficial consumption, or beneficial consumption. However, the case studies indicate that in the absence of controls over water consumption (e.g., through WCPs), WCTs generally promote higher beneficial water consumption. Where a WCT results in increased beneficial consumption of water upstream, a Pareto improvement is possible only if parallel conservation of equal or higher magnitude occurs through reductions in nonbeneficial consumption or nonrecoverable return flows, which are then allocated to downstream users whose supplies would otherwise be reduced by the increased upstream consumption. This presents a significant challenge in closed basins where return flows are recoverable (i.e., nonrecoverable return flows are nonexistent or marginal), because return flows are valuable and already allocated to downstream uses, and opportunities to reduce nonbeneficial consumption without negatively impacting biomass production have been largely exhausted (Perry et al. 2009). Perhaps not surprisingly, in *all* case studies where return flows are recoverable and water conservation is achieved, it results from a decrease in water consumption that is due to WCPs that constrain water availability and consumption (e.g., charges, quotas). In such cases, WCTs can be viewed as being a *response* to WCPs—that is, they are adopted to mitigate income losses from reduced consumption due to the WCP (Crase, O'Keefe, and Dollery 2013).

Where return flows are not recoverable, WCTs will conserve water and lead to a Pareto improvement if water withdrawals are reduced. Although WCTs appear to be more effective in achieving water conservation under nonrecoverable return flow regimes than under recoverable return flow regimes, more empirical evidence is needed concerning the behavioral responses of water users before drawing firm conclusions about the ability of WCTs to effectively conserve water in this context.

Trade-offs

We next examine the relationships and trade-offs between agricultural income, water consumption, and water conservation.[7] Our review reveals a positive correlation between income and water consumption in 86.6 percent of the 134 case studies for which information on the two variables is available. The data show that the higher income following WCT adoption generally results from higher water consumption through expanding acreage, supplementary irrigation, or shifting to higher value (and more water intensive) crops. We find a negative correlation between income and water consumption in only 4.5 percent of the case studies. In these studies, reduced water consumption was enforced through complementary policies (especially quotas). At the same time, income increased through the use of best available WCTs, which reduced nonbeneficial consumption and/or nonrecoverable return flows, thus

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[7]See the online supplementary material for summaries of these results and details concerning the database.

allowing the farmer to partially offset water consumption reductions due to WCPs (Yan et al. 2015). Income also increased through reduced production costs (Qureshi et al. 2011).

We find a negative correlation between income and water conservation in 78.1 percent of the 128 case studies for which information on the two variables is available, and a positive correlation in 5.5 percent of the cases, while the relationship is ambiguous in the remaining 16.4 percent. As discussed earlier, water conservation can be achieved not only through reduced water consumption but also through reduced nonrecoverable return flows. The studies in which a positive correlation between agricultural income and water conservation is observed largely correspond to those in which the correlation between income and water consumption was negative (see previous paragraph). Notably, eleven of the twenty-one studies where the relationship is ambiguous involve nonrecoverable return flow regimes.

These results suggest that unless WCPs are in place to limit water consumption, WCTs typically increase agricultural income, but at the expense of increased water consumption and reduced water availability for other uses.

Lessons Learned from Experience with WCTs

The findings we have presented thus far were developed and discussed at a workshop on WCTs and WCPs held in Venice in October 2017. Attendees included experts from academia, the World Bank, the Organization for Economic Cooperation and Development, the UN Food and Agriculture Organization, EU regional and national institutions, and the European Commission.[8] Participants delivered presentations and were subsequently asked to identify successes and failures in current and past efforts to conserve water through WCTs at the least economic cost, based on their expertise and the evidence and literature presented at the workshop. In this section, we present a summary of the main areas of consensus reached during the workshop and follow-up discussions, with the aim of informing the debate on water conservation policy reform.

There is Sufficient Evidence on the Performance of WCTs

The available evidence on WCTs is generally presented in terms of performance indicators (e.g., the ratio of water consumed by the crop to water delivered to the field, or to total water withdrawals) at the field level (van der Kooij et al. 2013), which cannot be generalized to the scales that are relevant for successful policy design (e.g., irrigation district, basin). On the other hand, evidence from modeling- or questionnaire-based studies that assess adaptive responses from a decision unit above the field level (e.g., at the farm or basin scale) is scattered and case specific. Consequently, the scientific literature cites the paucity of quantitative data from rigorous research on WCTs as a significant barrier to the design of effective interventions for achieving water conservation (Lankford 2012). Indeed, if WCTs increase adopters' income, but the evidence on the impacts of WCTs on water conservation above the field scale is ignored, an analyst might conclude that large quantities of water can be conserved through WCTs while also increasing income, and thus find the implementation of WCTs to be justified.

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[8]The list of workshop attendees is presented in the online supplementary materials.

Fortunately, the number of studies examining the performance of WCTs that go beyond the field scale has grown significantly. In fact, of the 230 applied case studies conducted between 1976 and 2017 and presented in our literature review, ninety-seven (42.2 percent) were published in the last nine years (2010–2018). This empirical evidence base, which was summarized in the previous section,[9] strongly supports the theoretical framework presented earlier. In particular, the empirical literature confirms the generally positive correlation between agricultural income and water consumption predicted in the theoretical literature under commonly encountered conditions, using multiple methods, and with a wide temporal and spatial coverage.

Further research on WCTs is clearly needed to better inform policymakers. For example, all hydrological, economic, and integrated models require assumptions that limit their ability to predict policy impacts, and the application of more sophisticated methods (through, e.g., ensemble experiments) could be used to sample this uncertainty (IPCC 2014). There is also a continuing lack of empirical evidence on the transaction costs of water policy reform (Garrick, Whitten, and Coggan 2013). Despite these research needs, the consensus of past research still holds. That is, under conditions of water stress, it should be assumed that WCTs will most likely increase water consumption and reduce water availability for other users (Perry et al. 2009). Unfortunately, too many past and ongoing irrigation programs have assumed the opposite (Perry and Steduto 2017).

Flawed Policy Designs

WCTs are often designed to have a dual purpose: to stabilize (if not increase) agricultural production while conserving water (Grafton et al. 2018). However, the available theoretical and empirical evidence reviewed in this article indicates that the ability of WCTs to enhance local agricultural production and income is often at the expense of increased water consumption and reduced water availability for downstream uses. In fact, the theoretical and empirical research shows that the production and conservation goals are generally incompatible, unless complementary WCPs are implemented. This finding should come as no surprise: the Tinbergen Principle (Tinbergen 1952), formulated by the winner of the first Nobel Prize in Economics, states that "in order to achieve the targets set for a certain number of objectives, an equal number of instruments is necessary." This means that if the goal is to conserve water (target 1) while protecting agricultural production (target 2), two instruments are necessary—one for each target. Another Nobel Prize winner, Robert Mundell, suggests a complementary explanation for the poor performance of WCTs: the Assignment Principle, which states that an instrument should be assigned to pursue the objective to which it is best suited and that the same instrument should never be used to pursue a second target (Mundell 1962). When one of these principles is violated, unexpected behavioral responses in the form of increased consumption and reduced water conservation may arise.

These principles suggest that the failure of WCTs to achieve water conservation is actually the consequence of poor policy design. Interventions that promote WCTs to both stabilize (and/or increase) agricultural production and achieve water conservation violate the Tinbergen principle, because they rely on a single instrument—WCTs—to pursue two

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[9]This evidence is presented in more detail in the online supplementary materials.

targets. Such interventions also violate the Assignment Principle, because WCTs are usually less effective at achieving the objective of water conservation than alternative policies such as quotas (Gómez et al. 2017).

Policy developments in Europe and Australia

Recent policy developments in Europe and Australia support the argument that there is an inconsistency between stated policy objectives and the instruments chosen to pursue them. For example, the EU's Common Agricultural Policy (CAP) includes a proposal to increase the "share of irrigated land shifting to water efficient systems/practices" through the adoption of WCTs (OJ 2013). Performance will be measured through an indicator that relies on the classical efficiency method (i.e., ratio of water consumed by the crop or water delivered to the field to total water withdrawals). Based on the CAP reasoning, if technology A, with 50 percent efficiency, is converted to technology B, with 90 percent efficiency, existing water demand can be met with a fraction (50/90) of the original water withdrawn—for example, 100 versus 55.6 units—leading to the "conservation" of 44.4 units. As previously discussed, such an approach ignores potentially recoverable return flows. This means that unless the allocation entitlement is capped (to 55.6 in the example), we can expect an *increase* in consumption and thus a *reduction* in return flows and water availability to other uses. Ironically, an irrigator that complies with the CAP by adopting WCTs such as drip irrigation will be eligible to receive direct payments to reward her environmental performance—while in all probability the irrigator is actually reducing water availability elsewhere and intensifying competition for water.

Another example of the inconsistency between stated policy objectives and the instruments chosen to pursue them comes from Australia, where the government has already spent AUD 5 billion of the AUD 8.67 billion allocated to subsidize the adoption of WCTs. A government inquiry into the performance of WCTs found that improving irrigation efficiency through WCTs reduced return flows to the environment and that the water accounting framework underpinning the investment program was seriously flawed (Australian Parliament 2017). In a surprising development, the Department of the House of Representatives used examples of local benefits to assert that water was conserved. If anything, such examples of local benefits support the arguments we made earlier, namely that although WCTs can generate local benefits through increased consumption at a local level, they do so at the expense of reduced water availability elsewhere. The Department of the House of Representatives did not allocate further funding to investigate this issue, while continuing to fund the expansion of WCTs.

UN Sustainable Development Goals

It is also important to note that although the UN's sixth Sustainable Development Goal formally aims at "ensuring availability and sustainable management of water and sanitation for all," it also calls for a reduction in water withdrawals through increased water use efficiency, which the UN defines as "the ratio between estimated plant water requirements (through evapotranspiration) and actual water withdrawal"—that is, classical irrigation efficiency (UN 2015). This target ignores potentially negative impacts of increased water consumption on water availability to third parties, including the environment.

Role for international organizations

International organizations that provide loans for infrastructure projects can play an important role in better informing and more effectively guiding decisions about water policy design in recipient countries. For example, the World Bank's new Environmental and Social Framework requires the borrower to "develop, maintain, monitor and periodically report a detailed water balance" to assess the performance of WCTs and other resource efficiency interventions, and the inclusion of "alternative water consumption offsets to maintain total demand for water resources within the available supply"—that is, WCPs (World Bank 2017, 40).

Role for the judiciary

The judiciary can also play a role in improving water policy design aimed at water conservation. For example, the U.S. Supreme Court recently ruled against the State of Wyoming for allowing "pre-1950 water appropriators to increase their net water consumption by improving the efficiency of their irrigation systems," thus breaching an agreement to share water from the Tongue and Powder Rivers with the State of Montana (Barton 2018). The seven-page judgment included estimates of the extra consumption of water resulting from the introduction of WCTs in the State of Wyoming and awarded compensation to the State of Montana.

The Search for Policy Solutions

If WCTs by themselves actually worsen rather than alleviate water scarcity, researchers and policymakers need to identify and develop policy recommendations that align individual behavior and collective goals in a cost-effective way. The literature on WCPs (e.g., quotas, buybacks) is consistent with the empirical findings we have presented in confirming the effectiveness of these instruments in conserving water. The WCP literature also warns about the potential for large costs in the design and implementation of such policies.

   Economic theory suggests that the optimal WCP would be to charge the resource at the margin in accordance with the social cost of water (i.e., the private cost plus negative externalities). Such a policy would render any other WCPs unnecessary and distortive. However, actually implementing socially efficient charges can be "impractical on technical and political grounds" (Fishman, Devineni, and Raman 2015). For example, the immediate response of irrigators to higher charges is usually resistance to reform (Gómez et al. 2017). Charges may also be technically infeasible, particularly in developing countries, due, for example, to the lack of metering devices (Dono, Giraldo, and Severini 2010); indeed, in rice systems where large quantities of water flow from field to field and through the saturated zone, metering is at present technically infeasible. Higher water charges will also reduce agricultural income and encourage investment in WCTs precisely to increase the consumed fraction of water withdrawals, to increase yield and mitigate income losses. These practical challenges may justify reliance on 'second-best' policies, where public support and subsidization may be warranted on social welfare grounds.

The Argument for Second-Best Solutions

For several reasons, quotas that assign a proportion of available water resources to users can be an effective option for addressing some of these challenges. First, quotas are generally less technically complex to design and implement than charges. For example, quotas do not require an accurate estimate of the price elasticity of water demand, which drives the responses to charges. Second, by imposing a proportional cap on water users, quotas avoid equity issues that arise from the reallocation of the resource to more productive users, thus making it easier to achieve consensus among irrigators (Ostrom 2007). This in turn means that for a given conservation target, a proportional cap on withdrawals will penalize productive irrigators and reduce agricultural income relative to charges, which encourage conservation in the least productive areas (i.e., those less profitable and therefore less likely to afford the incremental charge). Moreover, under some specific circumstances, quotas may be an ineffective tool for conserving water (Molle 2009).[10]

Both quotas and charges "involve a wealth transfer from agricultural water users to society and are typically met with resistance" from irrigators,[11] which increases "transaction costs that may delay or block progress toward efforts to conserve water" (Pérez-Blanco and Gutiérrez-Martín 2017). The reacquisition of water by water management institutions through buyback programs has gained momentum in some countries, including Australia, the United States, and Spain, as a way to overcome resistance to reform (Crase, O'Keefe, and Dollery 2013). Buyback programs establish a bidirectional wealth transfer, whereby society benefits from water conservation and agricultural water users receive financial compensation (i.e., the beneficiary pays). More specifically, buyback programs operate through permanent or temporary markets in which public institutions issue purchase tenders to compensate those farmers who relinquish their water allocation. On the other hand, buyback programs can place a significant burden on public budgets, particularly when there is overcompensation due to information asymmetries (Pérez-Blanco and Gutiérrez-Martín 2017). Water buyback programs may also conflict with national and supranational regulatory frameworks. For example, the Polluter Pays Principle dominates EU water legislation (OJ 2000) and EU institutions have filed lawsuits against beneficiary pay-based interventions in the past (Lindhout, den Broek, and Berthy 2014).

From Panaceas to Actual Solutions

All of the WCPs we have discussed—charges, quotas, and buybacks—share a common feature: achieving the water conservation target comes at the expense of reduced agricultural water consumption, which generally involves costs for water users and institutions due to lower agricultural production, and related compensation where applicable. Thus, the sustainability objective may conflict with economic growth and poverty reduction objectives. However, the choice, design, and implementation of sensible regulatory and economic mechanisms can help mitigate the negative impacts of WCPs on income. For example, quotas

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[10]One such circumstance would be when irrigators react to irrigation rationing on certain days of the week by increasing water use during unrestricted days.

[11]Of course, the original water rights granted to irrigators represented a transfer of wealth in the opposite direction.

that limit water consumption can be coupled with water markets to allow the reallocation of water toward more productive uses, thus mitigating negative impacts on aggregate production while conserving water. In addition, the use of WCPs encourages farmers to increase yields and income through autonomous on-farm adaptation such as use of better crop varieties or minimization of nonrecoverable return flows and nonbeneficial consumption (Gómez et al. 2017). In fact, effective enforcement of quotas has made Israeli irrigated agriculture among the most productive in the world per unit of water applied or consumed. Similarly, the enforced water scarcity experienced by farmers in parts of northwestern India historically resulted in the country's highest yields per hectare, even though water availability was the lowest (Perry and Steduto 2017). These examples suggest the possibility of achieving improvements in allocative efficiency (through autonomous on-farm adaptation) along with increased water conservation (e.g., through quotas), where inequitable outcomes can be addressed through policy interventions that ensure that every agent in the economy is better off.

The effects of WCPs on agricultural income and water conservation also depend on the evolution of key macroeconomic variables such as crop prices. WCPs implemented at a large scale will change regional and national agricultural production and supply, thus affecting input and output prices in the agricultural sector. However, at a global level, the impact of WCPs is expected to be limited due to intra- and international commodity trade, even where the local impacts are large (Hertel and Liu 2016).

The theory and empirical evidence presented here suggest that WCPs can achieve the objective of water conservation at a lower cost than WCTs. In fact, if the objective is to enhance water conservation while limiting income losses in the agricultural sector, there appear to be "much more cost-effective options to achieve this goal" than WCTs (Qureshi et al. 2011). On the other hand, a complete assessment of the cost-effectiveness of WCPs must account for the total costs of these policy options, which include not only income losses, but also the transaction costs of the policy change. From this perspective, WCTs can still be part of a cost-effective policy mix provided they help to reduce the transaction costs of transitioning toward adoption of WCPs that effectively conserve water (Garrick, Whitten, and Coggan 2013). WCPs such as quotas or buybacks thus become the true catalyst for water conservation, with WCTs playing a complementary, facilitative role. But sequencing is critical: good WCPs encourage appropriate WCTs; subsidized WCTs, without appropriate WCPs, are an expensive road to increased water scarcity.

Adherence to the myth that one "can adapt to changing conditions by focusing primarily on increasing irrigation efficiency" through WCTs "distracts discussion from the need for more sweeping changes in water institutions, infrastructure, and management" that enable and catalyze genuine transformational responses to water scarcity challenges (Hanak et al. 2009). While such sweeping changes include regulations and enabling infrastructures, it is particularly important to focus on investments to develop adaptive institutional systems that are robust and capable of adopting superior policy alternatives as new information becomes available.

Experience over the past fifty years warns against implementing WCTs, WCPs, or other interventions as panaceas for addressing complex environmental problems (Ostrom 2007). Environmental and water policies are creatures of design, and the available evidence indicates

that following their implementation, society may still be worse off if the costs of a policy and any residual welfare losses exceed the gains from its adoption. This is the case for several WCTs worldwide, where the benefits at the local scale come at the expense of higher water consumption by irrigation and reduced water availability for other uses at a basin scale; but this is also the case for WCPs such as water markets (e.g., in Australia), which have enhanced allocative efficiency among commercial users while reducing environmental flows (Gómez et al. 2017). Institutional, regulatory, and socioeconomic challenges emerge as the most serious barriers to the realization of water conservation opportunities. Unless these barriers are addressed, it is likely that water that might have been conserved will instead be incorporated into the agricultural process and consumed locally (e.g., following intensification or expansion of the agricultural process).

Conclusions

This article has presented an extensive review of the theoretical and empirical literature to assess whether the higher physical irrigation efficiency achieved through WCTs actually conserves water. Experience with WCTs suggests that if not complemented with behavioral policy tools (i.e., WCPs), agricultural WCTs typically increase local agricultural income and sometimes reduce water withdrawals, but usually increase water consumption, thus decreasing water availability for other uses. This makes WCTs economically inefficient from a Pareto standpoint. Because on-site agricultural income gains rarely generate the additional basin-wide economic benefits necessary to offset the costs of reduced water availability downstream and the investment costs, WCTs are also allocatively inefficient.

The true strength of WCTs is that within a context of constrained water availability, they facilitate increased agricultural production and income on-site and provide the basis to minimize the potential negative impacts of reduced water consumption. We conclude that sensible water policy design can build on WCTs to mitigate impacts on agricultural income and enhance the acceptability of effective WCPs. However, agricultural policy design should be used to encourage investments in WCTs in water-stressed areas only if downstream water availability for other productive uses and the environment is adequately protected, which requires a full understanding of current and future water flows.

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