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Viewpoint: Water, agriculture & poverty in an era of climate change: Why do we know so little?

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ABSTRACT

Understanding the complex relationship between water, agriculture and poverty (WAP) is essential for informed policy-making in light of increasing demand for scarce water resources and greater climatic variability. Yet, our understanding of the WAP nexus remains surprisingly undeveloped and dispersed across multiple disciplines due to conceptual (biophysical and economic) and measurement issues. We argue that water for agriculture will need to be better managed for it to contribute to reductions in poverty and vulnerabilities. Moreover, this management will need to consider not just quantities of water, but the quality of the water and the multiple agricultural and non-agricultural uses. For this reason, expanding research in WAP needs to involve interdisciplinary efforts. We identify three key knowledge gaps in WAP that are particularly pressing in light of greater climatic variability. These are climate change adaptation, over-abstraction of groundwater, and water quality.

1. Introduction

Population pressures and economic development are increasing demand for scarce water resources for competing uses. At the same time, greater climatic variability means that there is more uncertainty in terms of availability of water. The impacts of greater water scarcity and climatic variability are unlikely to be evenly distributed. Poor and marginalized populations, especially rural smallholders, are more likely to be negatively impacted. As such, we need to better understand the relationship between water and poverty. Moreover, since 70% of human consumption of freshwater is used for agriculture, we need to better understand the complex relationship between water, agriculture and poverty (WAP) in order to generate rigorous evidence for informed policy-making.

Yet, our understanding of the WAP nexus remains surprisingly undeveloped and dispersed across multiple disciplines (Jacoby, 2017). Agricultural economists, for example, have tended to neglect water in the last decade or so. Literature that focuses on the agriculture-poverty link tends to take water as a given input (e.g. “rainfed agriculture”) and analyses the adoption of variable inputs (e.g. seeds, fertilizer, herbicides, etc.) conditional on land and water. For example, of the 12 articles in the 2017 special issue of *Food Policy* on agriculture in Africa, only one mentions water (aside from the overview article), and even that is just a brief report that the incidence of irrigation is quite small (Sheahan and Barrett, 2017). Similarly, resource economists have focused on the management of water resources in agriculture using prices or water rights from the perspective of increasing allocative efficiency, and internalizing externalities (Dinar and Mody, 2004; Bar-Shira et al., 2006; Tsur et al., 2004; Rosegrant and Binswanger, 1994; Garrick et al., 2013). That is, they focusing on the water-agriculture link. This does not explicitly address poverty concerns, especially if increasing allocations of water towards uses with higher net returns means diverting water away from poorer populations.

Most of the economics literature that examines irrigation focuses on whether farmers have access to irrigation water (Bhattarai, 2003; Gebregziabher et al., 2009; Huang et al., 2005; Huang et al., 2006; Mekonnen et al, 2019; Passarelli et al, 2018), rather than on the quantity, timing and/or quality of the water that they use. Comparatively speaking, more attention has been devoted to examining the adoption of irrigation technologies (e.g. Carter et al., 2016; Fraiture and Giordano, 2014; Nakawuka et al., 2018; Namara et al., 2014). Much less attention has been paid to the effect of irrigation on incomes (e.g. Achempong et al., 2018; Adeoti et al., 2009; Balana et al. 2019; Dillon, 2011; Huang et al., 2005; Hussain and Hanjra, 2004), and on production diversity, food consumption and nutrition (e.g. Burney and Naylor, 2012; Burney, et al., 2013; Domènech, 2015; Pandey et al, 2016; Buisson and Balasubramanya, 2019).

The tendency to focus on just parts of the WAP nexus is mirrored in the literature on the water-energy-food nexus. This literature tends to focus mainly on the energy-food link where it addresses questions of how easing access to energy through subsidies impacts cropping decisions and farm incomes by easing access to groundwater for irrigation

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(e.g. see Mukherji et al, 2012; Badiani et al., 2012; Badiani-Magnusson and Jessoe, 2018; Bardhan et al., 2012; Birner et al. 2011; Janakarajan and Moench, 2006). More recently, this literature has examined the suitability of solar pumps (e.g. Schmitter et al., 2018; Worqlul et al., 2017) and the effect of this energy-related technology on food production and incomes (e.g. Burney et al., 2013).

Understanding the role of water in agriculture and poverty is important, especially if irrigation reduces risks faced by farmers. With climate change, irrigation and water storage are likely to become more instrumental in providing enabling conditions to reduce vulnerabilities. Irrigation was an important element of the Green Revolution; combined with improved seeds, fertilizers, and pesticides. Asian countries especially witnessed impressive increases in agricultural productivity and reductions in poverty (Alaofè et al., 2016). However, in light of climate change, water cannot just be an input that is taken as given in agriculture. Water for agriculture will need to be better managed for it to contribute to reductions in poverty and vulnerabilities. This management will need to consider not just quantities of water, but the quality of the water and the multiple agricultural (e.g. staples vs. cash crop) and non-agricultural uses. For this reason, expanding research in WAP needs to involve interdisciplinary efforts.

We suggest that there are good reasons for this apparent neglect that center around conceptual issues (Section 2) & measurement issues (Section 3). In Section 4, we discuss important and pressing knowledge gaps that follow from the lack of attention paid to the WAP nexus.

2. Conceptual issues

Given the complexity of the natural and social sciences embedded in the WAP nexus, an interdisciplinary approach is essential to better understand how agricultural water management and use affect poverty. While interdisciplinary approaches are also important for shedding light on the links between other agricultural inputs (e.g. labor, land, seeds, fertilizers and agrochemicals) and poverty, water is fundamentally different in that it is a mobile resource that often moves freely between properties over which people have claims, is difficult to measure and control, and has many different uses (Meinzen-Dick, 2014; Rogers, et al., 1998). Simultaneously achieving the Sustainable Development Goals (SDGs) of "ensuring the availability and sustainable management of water…for all," of "promoting sustainable agriculture," and of "ending poverty in all its forms" (UN General Assembly, 2015) will necessitate that irrigation engineers, hydrologists, economists, and other social scientists among others work ever more closely together to understand how these complex physical and social systems interact.

A number of conceptual issues, however, presents challenges to interdisciplinary approaches to research on WAP, as well as to disciplinary research on this topic, especially for economists. To help us focus ideas, it is helpful to recognize that agricultural water management is fundamentally a complex multidimensional optimization problem that balances the biophysical supply of water with economic and social demand for the resource. For practical purposes, however, various disciplines reduce it to a unidimensional optimization, and do not always choose the same dimension, scale, and/or time frame. A consequence of this is that natural scientists tend to focus on ways of optimizing the supply of water, while social scientists tend to think about the demand side and how water is (optimally) allocated and used. Because their entry points are different, various disciplines address different components of the WAP nexus and concern themselves with different objectives, some of which are not necessarily consistent with poverty reduction.

We break these conceptual challenges down into (1) biophysical issues and the related debates within and among irrigation engineers, hydrologists, and economists about water use and 'efficiency'; and (2) economic issues and how assigning prices and allocating property rights to a complex resource like agricultural water may affect how water resources are managed, which in turn may affect social welfare and/or poverty reduction objectives.

2.1. Conceptual challenges – biophysical issues

Although the focus of hydrologists and irrigation engineers is on the broader supply of water, they tend to have limited agreement around key conceptual issues because the "science of hydrology and the practice of irrigation have developed at different scales" (Perry, 2007). In the practice of irrigation, for example, getting water to the crop is the main objective, and hence the aim is to make sure that water diverted from various sources is used to the greatest extent possible for crop cultivation. Hydrologists, on the other hand, study stocks, flows, and losses of water at larger landscape scales (such as a basin, country or even world) over longer periods of time, with the objective of maximizing the availability of water for increasing numbers of agricultural and non-agricultural uses.

The practical consequence for irrigation engineers is that they design irrigation systems in order to maximize the 'efficiency' of agricultural water use by minimizing the share of source-diverted water that does not flow to crops. Of course, these designs depend on how efficiency is conceptualized. The classic definition of irrigation efficiency – the ratio of irrigated water consumed by the crop relative to the water withdrawn from a source (Israelson, 1950) – has been modified over time to account for differing notions of water consumption (e.g. evapotranspiration[1] of water and the water necessary for maintaining leaching to control soil salinity; Jensen (1967)) and to assess losses in the conveyance (ratio of water delivered to the field relative to water delivered to the distribution system) and application (ratio of irrigation water consumed by the crop relative to the water delivered to the field) of irrigated water. Further modifications address limitations related to the denominator (water supplied) by accommodating for return flows (i.e. irrigated water that flows back to drains and rivers that can be reused downstream or as groundwater; see Bos and Nugteren, 1974; Bos and Nugteren, 1982; Jensen, 1993; Willardson et al., 1994; Allen et al., 1997; Willardson and Allen, 1998, Perry, 2007) and for water quality (Keller and Keller, 1995). The take away from this is that the many different definitions of irrigation efficiency reflect a "widespread confusion in the literature about what constitutes 'water use'" in irrigation (Perry, 2007).

The implication of hydrologists' focus on assuring water availability at, say, the basin level is that they devise interventions that are intended to decrease the extent to which natural runoff is diverted from 'beneficial' consumptive uses, and to reduce evaporation (which could leave the basin). Thus, even in irrigated systems, reducing runoff and evaporation are the primary entry points for hydrologists because they are considered 'non-beneficial' uses of water or 'losses' (in conversation with colleagues at the International Water Management Institute (IWMI)). Keeping water at the center, hydrologists thus seek to maximize the availability of water, and sometimes seek to maximize the uses of water.

The differing objectives of hydrologists and irrigation engineers can conflict. For example, by using 'efficient' systems such as drip irrigation, it is possible for farmers to reduce the volume of water that they deliver to the field without sacrificing the amount of water consumed by the crop. The resulting increase in 'application efficiency' may however come at the expense of water availability at the basin level if return flows are also reduced. Further, it is worth noting that none of the irrigation efficiency concepts takes farmers' decisions about crop production into account, and hence efforts to achieve any of these forms

[1] The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants. The former is viewed as a non-beneficial 'use' of water from the perspective of the river basin, while the latter is considered a beneficial use of water for consumptive purposes.

of efficiency do not necessarily imply good performance. For example, if farmers supplied significantly less water to a field than the crop would normally ‘consume’, then irrigation efficiency would be high, but yields would be low (Hansen, 1960). In this context, one could argue that the purpose of irrigation fails (Perry, 2007).

Recognizing that farm- and irrigation system-level efficiency measures may be inappropriate tools for basin-level water management and planning, and that agriculture is the largest user of water resources worldwide, Seckler (1996), an economist, proposed a measure of ‘agricultural water productivity’ (amount or value of crop production per unit of water applied or transpired) in an effort to identify ways to achieve ‘real’ efficiency gains and ‘real’ water saving at various levels (Giordano, et al., 2017). The idea is that increasing water productivity, or getting ‘more crop per drop’ by growing more food with the same amount of water or less (Moulden, 1997), can help to alleviate water scarcity, achieve food security, and reduce strains on the environment (Rijsberman and Molden, 2001). Analyses that focus on maximizing water productivity, especially in arid and rainfed areas (e.g. Amarasinghe and Smakhtin, 2014) have featured prominently in the hydrology and water management literature despite recognized limitations of the approach (e.g. underplaying water quality, ignoring non-crop water uses, and environmental uses; IWMI, 2004).

Perhaps the most compelling limitation of the emphasis on maximizing water productivity is that water productivity is just a single-factor average productivity measure in a multi-factor and multi-output production process (Barker et al., 2003). Indeed, there is no underlying conceptual rationale for maximizing an average water product since profit-maximizing farmers will make decisions at the margin, and will simultaneously choose other inputs in order to achieve this objective (i.e. by equating the marginal benefit and marginal cost of each input), rather than to maximize how much crop can be produced per drop of water (Wichelns, 2014). As Wichelns (2015) notes “simple ratios of water productivity or water footprints contain too little information to guide stakeholders in their deliberation of reallocation decisions.” While recognition of this has helped to shift thinking from water productivity as a “principle objective” to water productivity as an “entry point” to understand limitations to water access and availability (Vidal et al., 2014), the challenge remains that the economic principle of profit maximization is difficult to apply to water management since the marginal cost of water faced by farmers is often artificially low or even zero (e.g. in surface irrigation systems and in groundwater systems where electricity is subsidized). Thus, in the absence of practical alternatives, considerable research efforts continue to focus on ways to maximize water productivity as a single way to address the challenges of climate variability.

2.2. Conceptual challenges – economic issues

While hydrologists and irrigation engineers concern themselves with the water-agriculture link in the biophysical space, their emphasis on the supply of water does not systematically address the link with poverty, which is in the economic space. Given that maximizing water productivity or availability for use does not imply that social welfare (or even income) is necessarily maximized, much less that poverty is minimized (Wichelns, 2015), it is not surprising that economists and irrigation practitioners struggle to find common ground even when they share a common underlying goal of improving the livelihoods of the poor. Even within economics, different streams focus on different pieces of the WAP nexus. For example, agricultural and development economists[2] often relegate water to a given input, and focus on topics related to the agriculture-poverty link. Environmental and resource economists doing research in developing countries, on the other hand, focus on the water-agriculture link (returns to agriculture under alternative water management regimes).[3]

2.2.1. Water prices

One challenge to interdisciplinary work on WAP is that economists, engineers, and other social scientists are far from agreement on the central role of agricultural water prices because they conceptualize them in different ways (Tsur, 2005). For the economist focusing on the demand side, the main concern is achieving efficient allocations of currently available water (in both irrigation schemes and farmer-led irrigation[4]), which are characterized by the marginal benefits of the last units of water used for particular purposes being equal to the marginal economic cost of that water. In competitive markets, prices serve to equate the marginal benefits and marginal costs. In the absence of water markets, however, achieving efficiency requires some sort of deliberate marginal-cost pricing to reflect scarcity values so that water may be allocated to the most economically valuable uses[5] (Dinar and Subramanian, 1998; Tsur et al., 2004).

For the irrigation engineer, a major concern with irrigation schemes is often cost recovery in order to sustain the supply of irrigation services. This requires incorporating fixed (design, construction) and variable costs (system operation and maintenance costs, service costs, depreciation) into water prices (Abu-Zeid, 2001; Barakat, 2002; Molle, 2009). Consequently, rather than representing marginal economic costs, such prices represent average delivery costs (Dinar and Mody, 2004), and are unlikely to result in efficient allocations within the schemes (Tsur et al., 2002). Paradoxically, irrigation engineers are silent on the cost-recovery of subsidies provided for purchasing pumps and equipment in farmer-led irrigation. Moreover, it is not clear that farmer-led irrigation approaches are universally equity- and justice-enhancing since the jury is out on whether poor smallholders are able to access irrigation as easily as better-off farmers can (Lefore et al., 2019).

For other social scientists concerned more with equity and justice objectives of irrigation schemes, progressive block price systems may have an appeal. The idea is that by charging higher volumetric prices for larger users (in higher blocks), a minimum quantity of water can be provided at lower prices (in lower blocks) to households that use small amounts of water. These latter are commonly assumed to be the poorest households. The success of these systems, however, depends on the strength of the relationship between income and water use. While less is understood with regard to demand for irrigation water in the developing world, there is some evidence that although this relation is positive for domestic water in developed countries, it is weak (e.g. see Nauges and Whittington, 2017). In other words, the distinction that small water users are poor and that large water users are rich is not strong. Nonetheless, Klaiber et al. (2010) do find that demand for residential water is more inelastic for larger users than for small users, indicating that price differences affect small users more than large users. While this evidence is suggestive that block pricing may not be an effective means of targeting low income households, more research in developing countries is needed to understand the potential for

[2] Development economics focuses on many topics beyond agriculture, where water may be a unit of inquiry, but this article only focuses on agriculture.

[3] Environmental economics also focuses on water-poverty linkages, in the context of water, sanitation and health. This, however, is not a linkage with agriculture.

[4] Farmer-led irrigation typically implies farmers irrigating using groundwater tapped through private wells/tubewells. It is not uncommon for governments to promote farmer-led irrigation by providing subsidies for well drilling, pumps, and equipment. Farmers are then responsible for supplying water from their private wells to their fields.

[5] This requires information on opportunity costs and values of water in alternative uses (de Azevedo & Balter, 2005). When they are involved, externalities should also be included in the cost (Dinar and Mody, 2004). Theoretically, this suggests that the price of water would vary by crop, water quality, and season, among other factors (Tsur, 2005). This is an arduous, complex and demanding task that is rarely feasible from a practical perspective.

irrigation water block pricing to achieve equity objectives there. Further, pervasive fragmentation of land holdings and extensive tenancy in the developing world may render the levying of asset (land)-based progressive pricing challenging. Finally, such systems may come at the expense of both cost-recovery, particularly in countries where there are many poor smallholders (Ruijs et al., 2008), and efficiency (see Boland and Whittington, 2000 for results pertaining to residential water in developing countries; as discussed below, it is not obvious if prices will indeed lead to efficiency-enhancing outcomes, and whether second-best objectives such as cost recovery and fees for accessing a resource may be more desirable).

While economists may agree on the allocative role of water prices, and that these prices need to be deliberately set by authorities to reflect scarcity values in the absence of well-functioning markets, there is not one preferred way to go about setting them in practice. The various methods include volumetric (which measures water consumed), output/input (a fee is paid on each unit of input used or output produced), and area pricing (depending on crop type, season, irrigation method, etc.); block rates (type of volumetric pricing); and two-part tariffs (which includes a fixed charge) (see Tsur and Dinar, 1997). Which methods are preferred on efficiency grounds are likely to depend on their respective implementation and monitoring costs (Tsur, 2000; Iglesias and Blanco, 2008), and on political feasibilities. Unfortunately, there are no robust methodologies for evaluating the effects that these implementation costs have on allocative efficiency (Iglesias and Blanco, 2008; Johansson et al., 2002). Consequently, it is not obvious whether implementing volumetric pricing would indeed lead to an efficiency-improving outcome if the real implementation costs are very high.

With growing concerns over water scarcity and falling groundwater levels in the presence of climate change and population growth, irrigation experts of all stripes tend to recognize that prices may be an appropriate tool for water demand-management. Indeed, one commonly cited goal for prices is to reduce agricultural water use (or to improve conservation). Microeconomics informs us that the success of this will depend on the price elasticity of demand, which is often low (Dinar and Mody, 2004; Gómez-Limón and Riesgo, 2004; Varela-Ortega et al., 1998; Gómez-Limón and Berbel, 1999; Feijoó et al., 2000). This means that demand for water is not very sensitive to price changes in the short term, and that water prices may in fact have a limited role in reducing water use. Moreover, increases in water prices may actually increase the total demand for water in the long term (Massarutto, 2002; Dinar and Zilberman, 1991). The reason for this is that while higher water prices may encourage farmers to use less water on their current plots and crops (intensive margin), the more efficient irrigation methods that they adopt (e.g. drip irrigation over sprinkler systems) may also give them incentives to increase their cultivated area and/or shift to more high-value water-intensive crops (extensive margin) (Massarutto, 2002; Dinar and Zilberman, 1991). Further, adjusting prices may not be effective means of reducing water use in climatic situations where water supplies are reduced temporarily (e.g. droughts) (Mejias et al., 2004; Salman et al., 2002). In short, prices may not be an effective water-management tool on their own. Reducing agricultural water use in response to climate variability and/or persistent water stress may require a system of quotas along with water prices (Molle, 2009; Dinar and Mody, 2004; Perry 2001). Further research on combinations of quotas and/or water prices will be necessary to determine appropriate context-specific approaches that achieve reduced-agricultural-water-use objectives as well as equity and justice (e.g. poverty reduction) objectives.

Water prices may, however, have a role to play in allocating water to more efficient uses, which may in turn attenuate the impacts of climate change on GDP. Based on global macroeconomic models of the status quo, The World Bank (2016) estimates that water-related climate damages will be 0.5% of global GDP in 2050, and that a disproportionate share of this burden will be concentrated in the developing world. They also find that allocating water to more efficient uses (mostly through pricing) could eliminate these damages globally, and might even lead to regional gains. Since irrigation is one of the largest uses of water in the world, such pricing would have to encompass the agricultural sector. The challenge here, however, is the gap in our understanding of how these dynamic global models and findings correspond with micro-level behaviors and gains.

2.2.2. Water rights

While the importance of secure property rights in sustainable natural resource management is increasingly becoming recognized (Deininger, 2003; Meinzen-Dick, 2014), differing understandings of the role of water rights complicate policy reforms in practice. Irrigation experts, for example, primarily conceptualize water rights as a method for allocating water and delivering services. Their focus is on the technical and institutional feasibility of allocating rights, and hence water delivery (e.g. see Lewis and Zheng, 2019; Hoogesteger and Wester, 2017; Zwarteveen, 1997). Economists, in their focus on efficiency, consider water rights to be important for more than just securing access to water as irrigation experts do. To them, water rights are also necessary for efficiency enhancing trade, and can also be an important mechanism for resolving the collective action problems (e.g. over-extraction) associated with managing common-pool resources characterized by costly exclusion and rivalrous consumption. For the former, water rights need to be tradable (Rosegrant and Binswanger, 1994). Moreover, in order for such transactions to take place, land and water rights must be separable (one can sell her water while keeping her land), the social benefits generated from the trade must be greater than the transaction costs, and water use needs to be metered (Michelson and Young, 1993; Rosegrant and Binswanger, 1994; Lewis and Zheng, 2019). For the latter, assigning water rights can change the structure of the collective-action problem (Hanna, 2003; Ostrom, 2003) by providing incentives for careful management. Their ability to do so however depends on the strength of the institutions that enforce them and the degree to which they are understood (Meinzen-Dick, 2014). Four of Ostrom's (1990) design principles for governance of irrigation systems are particularly relevant here: clearly defined boundaries, monitoring, graduated sanctions, and conflict resolution mechanisms (Meinzen-Dick, 2014). In the more information-rich environment of surface irrigators, where observation and experimentation allow irrigators to monitor other irrigators practices and to understand the boundaries, capacity and variability of the system, irrigators are more likely to develop local norms and rights for water management (Schlager, 2007; Uphoff, 1986, 1992). Establishing water rights among individual small-scale users of groundwater is more challenging however as irrigators are not likely to understand the boundaries, capacity and variability of the "invisible resource" that they extract, nor observe the practices of other irrigators (Schlager, 2007; Rose et al., 2002). In contrast to irrigation experts and economists, other social scientists regard water rights as a way of empowering individuals, especially the poor and vulnerable, and focus on equity as an important consideration for sound water resource management (Molle, 2004; Zwarteveen, 1997; Zwarteveen and Meinzen-Dick, 2001).

A central question is whether tradable water rights and markets for water do in fact lead to more efficient allocations of water through trade. A series of studies in the economics literature poses this very question by examining tradable water rights in developed (United States and Australia) and developing countries (China, Chile and Mexico) and focusing on whether there have been improvements in intra-agricultural and inter-sectoral allocative efficiency in the presence of transaction costs. The findings are mixed (see Bauer, 1997; Michelson and Young, 1993; Grafton et al., 2011; Grafton et al., 2012; Colby, 1990; Garrick and Aylward, 2012; Young et al, 2009). The reason for this could be that water rights in these countries were initially allocated in such a way that they were already efficient. That is, there were few gains to be had from trade, and hence little opportunity to make efficiency-enhancing trades. It is more likely however that the potential social benefits generated from water trades tended to be swamped by the transaction costs associated with them, and hence trades that would have taken place in the absence of these transaction costs did not in fact take place. Our understanding of this effect depends in part on different considerations of what transaction costs are (Garrick et al. 2013). Most studies have focused on static transaction costs (e.g. Archibald and Renwick, 1998; Lund, 1993; Ruml, 2005), which are those costs associated with search, negotiation, etc. within a given institutional structure. But there are also dynamic costs such as institutional transition (moving from the current institution to a new structure) and institutional intertemporal lock-in (characteristics of current institutions that limit future flexibility, such as vested interests of current water rights holders) costs that are associated with institutional change (Marshall, 2005). It is worth noting that in an era in increased weather variability due to climate change, these dynamic costs are likely to grow if, for example, caps in cap-and-trade systems need to frequently be adjusted due to changing expectations about rainfall. Less attention has been paid to these dynamic costs (e.g. see McCann and Easter, 2004; Garrick and Aylward, 2012), and the results from evaluations based on static costs alone may be very different as more information on dynamic costs is gleaned over time (Garrick et al., 2013; Carey and Sunding, 2001). The upshot is that if the first-best efficiency goals attached to water markets and allocation reforms are hindered due to transaction costs, then other second-best objectives (e.g. equity, sustainability, etc.) may be more appropriate as policy priorities. Of course, the presence of high transaction costs may also hinder the attainment of these objectives as well. In addition, if smallholder farmers have to spend a lot of time accessing irrigation water, then they may be unable to participate in social protection programs such as work-for-food, etc.

Efficiency, equity and sustainability are important objectives for poverty alleviation. Yet, there are two major knowledge gaps in the water rights literature related to these linkages. The first is the linkage between water rights in agriculture and poverty. Even those studies that examine irrigation markets in China, Mexico and Chile do not address the distributional effects of water rights (e.g. see Bauer, 1997; Grafton et al., 2012; Hoogesteger and Wester, 2017; Rosegrant and Schleyer 1996; Schleyer and Rosegrant, 1996). Since transaction costs, especially the institutional transitional costs associated with policy reform, are likely to be higher in developing countries, understanding the welfare effects for farmers with tradable rights and for third-parties who may not hold rights (Grafton et al., 2012) is important for understanding whether water rights in agriculture can be a poverty-alleviation instrument. The second is that the focus of the water rights literature on water access and availability has come at the expense of rights to water quality. This is an important shortcoming considering how water quality links to health and poverty in complex ways (see Rohr et al. 2019 for a comprehensive review of the linkages between infectious disease and food production).

3. Measurement issues

Conceptual issues aside, challenges in measuring agricultural water use and quality in developing countries create obstacles to collecting the type of data needed for economic empirical analyses of the WAP nexus.[6] It is complicated enough to accurately measure land area/quality and agricultural production, and hence yields (Desiere and Jolliffe, 2017; Gourlay et al., 2017; Bevis and Barrett, 2020). It is even more difficult to measure the quantity and quality of agricultural water use given that water is a mobile resource, and as discussed in the previous section, there is no single agreed-upon definition of what constitutes "water use" in agriculture. Assuming that "water use" is defined as the quantity of water applied on a field or plot, part of the problem is that the most reliable way of measuring such agricultural water use – water meters attached to irrigation pumps – is costly and fraught with practical problems (e.g. non-agricultural uses of extracted water, meter tampering, etc.). It is not surprising then that whether farmers in developing countries receive their water from irrigation schemes or from individual wells, water pumps are rarely metered; and when they are, the meters typically record electricity use, a noisy measure for water abstraction, much less water used for agricultural purposes given the multiple uses of water (van Koppen, et al., 2006).

The consequence of this measurement challenge is that farm- and plot-level survey data typically employed by agricultural economists are generally not appropriate for addressing questions about the links between water use, agriculture and welfare outcomes. For example, we reviewed the household surveys conducted under the Living Standards Measurement Study - Integrated Surveys in Agriculture (LSMS-ISA) project, and found that agricultural water-related questions posed of farmers are few and far between. In most cases, farmers are only asked if their particular fields are irrigated, and if so, what that source of the water is. Given the care that the LSMS team dedicates to accurately measuring agricultural land, production, and other inputs, and given that the primary objective of the LSMS-ISA project is to "foster innovation and efficiency in statistical research on the links between agriculture and poverty reduction" in Sub-Saharan Africa (World Bank, 2019), the absence of more detailed measures of agricultural water use suggests that the measurement costs and practical challenges are prohibitively high for the LSMS team to consider this particular link between agriculture and poverty.

Alternative sources of data on agricultural water use are promising, but come with their own challenges. One particular source worth considering is remote sensing data. While economists are increasingly taking advantage of the wealth of satellite data available, economic analyses using water-related satellite measures other than rainfall (typically to measure shocks) are rare. In their comprehensive overview of applications using satellite data in economics (e.g. remotely sensed measures of agricultural land, crop choices, and natural resources such as forest cover, logging, and beaches), Donaldson and Storeygard (2016) have little to report on economic analyses of agricultural production using satellite measures of agricultural water use given to the paucity of such analyses. Nonetheless, spatially and temporally distributed estimates of evapotranspiration (ET) may hold promise as estimates of irrigation water use for economic analysis (Anderson, et al., 2012). Users must keep in mind, however, that since the smallest resolution for these data is currently a 1 km-by-1 km pixel, the unit of analysis for any study of water and agriculture in developing countries will likely need to be larger than the size of the farm. While this means that standard plot- and farm-level analyses may not be possible, it may also encourage agricultural economists to think at a more aggregate level that is in line with the boundaries of the water sources themselves (e.g. aquifers or basins), which are also the units of analysis for standard hydrological and resource economic studies. Further, high-resolution remote-sensing ET data are themselves noisy estimates of water applied to fields since they are better viewed as estimates of water consumed by crops, rather than water applied to fields as an input into the agricultural production process. To illustrate this point, consider a farmer who over-irrigates her plots to the extent that the water seeps below the root level and neither evaporates nor transpires. In this example, since not all of the water applied to the field is captured by ET measures, ET will underestimate the amount of water used by the farmer as an input.[7] In addition, actual ET rates depend not only on

[6] These difficulties also hinder the setting of water prices and the allocation of water use rights.

[7] This raises the specter that non-classical measurement error (NCME) is likely prevalent in measures of water use/consumption whether they are collected at the plot level or estimated by remote sensing. This can be particularly problematic if this measurement error is correlated with NCME of the variable

solar radiation, temperature, and relative humidity, but also on the type, structure, age and health of plants grown.[8] To the extent that there is error in measuring any of these inputs, there will be error in measuring ET. One particular challenge is establishing which crops are grown on the fields in the pixels under consideration since ET is different for different crops on the same fields under the same conditions. This is especially problematic in areas where farmers practice intercropping. More recent efforts to measure the timing and amount of irrigation by using optical and thermal Landsat-7/8 data have proven accurate at the time scale of an agricultural season, but less so for periods of two weeks or less (Olivera-Guerra, et al., 2020). With the planned launching of the Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA) mission in 2025, however, the availability of more frequently visited high-spatial resolution thermal data should improve the accuracy of these data, and could prove useful for research on WAP.

Another potential alternative source of data on agricultural water use can be collected by partnering with irrigation pump providers that attach meters to their pumps and monitor them. IWMI is experimenting with this approach by partnering with Futurepump Ltd. to develop a Real-time East Africa live groundwater use database (REAL-GUD) using the meters on the network of solar pumps that are sold and monitored remotely by Futurepump in East Africa. In addition, as information technologies become more accessible in developing countries, applications that use the Internet of Things (IoT) in agriculture are likely to provide a wealth of data on agricultural water use and quality. Loosely defined as internet-enabled communications between everyday objects, IoT creates opportunities for farmers in developing countries to adopt data-driven smart agricultural practices. Through IoT, sensors with wireless capabilities can be deployed on farms (e.g. in the ground and in water sources) to collect data that is stored in cloud systems or servers and made accessible to farmers by means of the internet or mobile phones. Partnering with irrigation pump providers who provide IoT services to farmers in developing countries[9] holds promise for analyzing the WAP linkages if carefully designed household surveys can be linked to these data.

Aside from the interest in the demand for and use of water, there are fundamental challenges in measuring the supply of water as well. Calculating 'stocks' and flows of surface or groundwater at a point in time is complex, especially given increasing weather variability due to climate change. Satellite data from the Gravity Recovery and Climate Experiment (GRACE) and the GRACE Follow On missions have proven promising by measuring gravity anomalies that can be attributed to surface and groundwater. The low resolution of these data (four degrees by four degrees), however, limits their usefulness for micro-level research on agricultural water availability. Given measurement issues on both the demand and supply side, it is no wonder that it is challenging to identify sustainable extraction use rates and paths.

4. Knowledge gaps

Understanding the role of water in agriculture and poverty is important, especially if irrigation reduces risks faced by farmers. Against the backdrop of climate change, water cannot just be an input that is taken as given in agriculture. Water for agriculture will need to be better managed for it to contribute to reductions in poverty and vulnerabilities. This management will need to consider not just quantities of water, but the quality of the water and the multiple agricultural (e.g. staples vs. cash crop) and non-agricultural uses. For this reason, expanding research in WAP needs to involve interdisciplinary efforts. We identify three key knowledge gaps in WAP that are particularly pressing in light of greater climatic variability. These are climate-change adaptation, over-abstraction of groundwater, and water quality.

First, the economic and human impacts of climate change on water resources are likely to be large (Hoanh et al., 2015). In the absence of adaptation measures, the effect of climate change on water resources is likely to result in lower national incomes in low- and middle-income countries (World Bank, 2016) and to exacerbate existing inequalities (Global Commission on Adaptation, 2019). Better-managed irrigation can be an important climate-change adaptation strategy in agriculture that supports improvements in yields and provides other benefits (Porter et al., 2014). Much of the analysis on adaptive measures, however, has focused on publicly-funded water-related infrastructure projects (World Bank, 2017). Less is understood about how adaptations in water management and autonomous responses at the micro-level, such as by farmers, take place (Jiménez Cisneros et al., 2014); and whether such measures improve reliable access to water, boost agricultural production, and reduce poverty. These measures include farm-level investments in efficient irrigation technologies, deficit irrigation, water harvesting, minimum tillage, and improved water delivery systems (Verchot et al. 2007, Luo et al., 2009, Piao et al. 2010). Rough estimates from global climate models suggest that GDP losses could be as much as a third greater in the absence of autonomous adaptation (ECONADAPT, 2015). Understanding the micro-level adaptive responses of farmers to climate change is important for ensuring that publicly planned adaptation investments have broader impacts (UNEP, 2018).

Second, although the over-abstraction of groundwater (when the water taken from aquifers is greater than the recharge, and hence groundwater levels fall) for agricultural purposes may be optimal for a given location at any point in time[10], it is likely that the rapid fall in groundwater levels observed in many regions is socially sub-optimal (e.g. ~1 m per year in parts of Jordan (IWMI, 2019); see also Molle and Closas, 2016; Villholth et al., 2016). Overexploitation of this nature follows from the challenges associated with managing this "invisible" common-pool resource as discussed in Section 2. While adopting water-saving technologies may be a necessary condition for reducing water use in agriculture, it is not a sufficient condition. Indeed, the use of more efficient irrigation equipment (e.g. drip irrigation) can lead to more water use as farmers increase their cultivated areas and/or shift to more high-value water-intensive crops (Massarutto, 2002; Dinar and Zilberman, 1991). The upshot is that in order to reduce the over-exploitation of groundwater, pumping and water-use behaviors in many regions will need to change. This raises a number of open questions that need to be addressed. For example, can nudges (Duflo et al., 2011) help to "correct" agricultural water-use behaviors, and if so, how large will the impacts be, and what will the distributional effects be? What role might quotas and tradable water rights play, and under what conditions

(*footnote continued*)
on the other side of the regression since the sign of the bias is ambiguous in this case. Abay et al. (2019) find that correcting just one of the sources of NCME can aggravate the bias in the estimator, however, and suggest that a second best approach of estimates based on multiple NCME may be preferable from a reduced-bias perspective.

[8] To further complicate matters, water applied to fields that is actually consumed by plants also depends on soil quality and its holding and drainage capacity. Efforts to account for soil color, moisture content, organic matter, and texture have been developed in order to more accurately measure albedo (He, et al., 2019) and hence evapotranspiration. Nonetheless there remain challenges to collecting high quality data on soils that can be used to accurately measure agricultural water consumption.

[9] Recognizing the potential for IoT in agriculture in developing countries, The World Bank sponsored a series of webinars "to highlight the innovation, business models, and demonstration of results on the ground for applying IoT in Agriculture" (https://olc.worldbank.org/content/internet-things-iot-agriculture-webinar-series).

[10] An optimal steady state level, where the rate of abstraction is equal to the rate of recharge, may be below the initial level. Thus, it may be optimal to over-abstract groundwater until the steady state level is reached (Jacoby, 2017).

might they be viable and effective at reducing water use, while also achieving poverty reduction objectives?

Rapidly declining costs of solar power generation are creating opportunities for small-scale farmers to either switch energy sources for pumping or to adopt groundwater irrigation for the first time. Combined with recent studies suggesting that there is plentiful groundwater in much of sub-Saharan Africa (You, et al., 2011; Schmitter, et al., 2018; Worqul, et al., 2017), this has led to a big push for expanding smallholder irrigation there using off-grid solar power. While there is some evidence that distributed irrigations systems such as these can significantly raise agricultural production, increase food security and reduce poverty among smallholder farmers (Burney and Naylor, 2012; Burney et al., 2013), the longer-term hydrological effects of a large uptake are not well understood. Interdisciplinary research will be crucial for understanding the conditions under which well drilling should be encouraged or discouraged, and where there are risks of over-abstraction. In regions such as South Asia where many farmers are connected to the grid and use subsidized electricity to pump water for irrigation and for sale to their neighbors, the effect of switching to solar powered pumps on water use and availability in water markets is not obvious. It is possible that providing farmers with opportunities to sell power back to the grid may not reduce water abstraction, and could lead to higher prices in secondary water markets, thus adversely affecting poorer households. This needs to be better understood before such policies are considered elsewhere.

Third, an important gap in the WAP literature is the question of how agricultural practices combined with agricultural water use and management affect water quality, and how this quality is explicitly linked to health and poverty outcomes. On the one hand, agricultural practices may affect water quality. For example, while agrochemical use may increase yields in smallholder systems, thus contributing to improvements in incomes and nutrition inputs, it may also affect water quality through runoff (Mateo-Sagasta et al. 2018; WWAP, 2017), thus compromising health outcomes over time through both infectious and non-infectious diseases (Lai, 2017; Ringler et al. 2018; Rohr et al., 2015; Sheahan and Barrett, 2017; Teklu et al., 2018). On the other hand, water quality may affect agriculture. For example, arsenic-contaminated water used for irrigation tends to accumulate in produce, especially rice (Rahman and Hasegawa, 2011), which can negatively affect cognitive functioning among those who consume it, and thus affect future earnings (Wasserman et al. 2004 demonstrated this for arsenic-contaminated drinking water). Farmers may find that the higher nutrient loads in untreated greywater used in agriculture can increase their yields, but this water source also poses severe health risks that include microbial diseases and toxicity (Dreschel and Evans, 2010; Evans et al. 2019; Gross et al. 2005; Malchi et al. 2014; Srinivasan and Reddy, 2009; Xie and Ringler, 2017; Yang et al. 2006). The expansion of dams and irrigated agriculture to support food production and improve livelihoods is also likely to affect malaria and schistosomiasis prevalence rates (Ijumba et al. 2002; Keiser et al. 2005; Kibert et al. 2010; Kibert et al., 2019; Steinmann et al. 2006; Yapi et al. 2005). Quantifying these tradeoffs and the impacts of management strategies that reduce these health risks is difficult due to feedback loops and measurement challenges (Liu et al., 2017; Sheahan and Barrett, 2017), but is important for informing policy.

In closing, despite the conceptual and measurement challenges that we outline above, there is an ever-pressing need for natural and social scientists to engage in collaborative research on WAP. The ability of the most vulnerable segments of society to navigate the consequences of climate change and population pressures depends on it and on informed policies. Moreover availability of and access to clean water will be instrumental to achieving many of the SDGs, not just SDG 6 ("Clean Water and Sanitation"). This research, however, will be costly and will require long-term financial commitments of the donor community. As such, this is not just a call to action to scholars, but is also a call to the donors.

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References

Abay, K., Abate, G., Barrett, C., Bernard, T., 2019. Correlated non-classical measurement errors, 'Second best' policy inference, and the inverse size-productivity relationship in agriculture. J. Dev. Econ. 139, 171–184.
Abu-Zeid, M., 2001. Water pricing in irrigated agriculture. Int. J. Water Resour. Dev. 14 (4), 527–538.
Achempong, D., Balana, B.B., Nimoh, F., Abaidoo, R.C., 2018. Assessing the effectiveness and impact of agricultural water management interventions: the case of small reservoirs in northern Ghana. Agric. Water Manag. 209, 163–170.
Adeoti, A.I., 2009. Factors influencing irrigation technology adoption and its impact on household poverty in Ghana. J. Agric. Rural Dev. Tropics Subtrop. 109 (1), 51–63.
Alaofè, H., Burney, J., Naylor, R., Taren, D., 2016. Solar-powered drip irrigation impacts on crops production diversity and dietary diversity in Northern Benin. Food Nutr. Bull. 37 (2), 164–175.
Allen, R.G., Willardson, L.S, Frederiksen, H., 1997. Water use definitions and their use for assessing the impacts of water conservation. In: de Jager, J.M., Vermes, L.P., Ragab, R. (Eds.), Proceedings ICID Workshop on Sustainable Irrigation in Areas of Water Scarcity and Drought, Oxford, England, 11–12 Sept., pp. 72–82.
Amarasinghe, U., Smakhtin, V., 2014. Water productivity and water footprint: Misguided concepts or useful tools in water management and policy. Water Int. 39 (7), 1000–1017.
Anderson, R.G., Lo, M.H., Famiglietti, J.S., 2012. Assessing surface water consumption using remotely-sensed groundwater, evapotranspiration, and precipitation. Geophys. Res. Lett. 39 (16).
Archibald, S.O., Renwick, M.E., 1998. Expected transaction costs and incentives for water market development. In: Easter, K.W., Rosegrant, M., Dinar, A. (Eds.), Markets for Water: Potential and Performance. Kluwer Academic, New York.
Badiani, R., Jessoe, K.K., Plant, S., 2012. Development and the environment: the implications of agricultural electricity subsidies in India. The J. Environ. Dev. 21 (2), 244–262.
Badiani-Magnusson, R., Jessoe, K., 2018. Electricity prices, groundwater and agriculture: the environmental and agricultural impacts of electricity subsidies in India. In: Schlenker, W. (Ed.), Agricultural Productivity and Producer Behavior. University of Chicago Press.
Balana, B., Bizimana, J.C., Richardson, J., Lefore, N., Adimassu, Z., Herbst, B.K., 2019. Water Resour. Econ. 100141. https://doi.org/10.1016/j.wre.2019.03.001.
Barakat, E.E., 2002. Cost recovery for irrigated agriculture: Egyptian experience. Available at: http://web.worldbank.org/archive/website00660/WEB/PDF/BARAKAT.PDF.
Bardhan, P., Mookherjee, D., Kumar, N., 2012. State-led or market-led green revolution? Role of private irrigation investment vis-a-vis local government programs in West Bengal's farm productivity growth. J. Dev. Econ. 99 (2), 222–235.
Barker, R., Dawe, D. Inocencio, A., 2003. Economics of water productivity in managing water for agriculture. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water productivity in agriculture: Limits and opportunities for improvement. Wallingford, UK: CABI; Colombo, Sri Lanka: International Water Management Institute (IWMI), pp. 19–35.
Bar-Shira, Z., Finkelshtainm, I., Simhoon, A., 2006. Block rate versus uniform water pricing in agriculture: an empirical analysis. Am. J. Agric. Econ. 88 (4), 986–999.
Bauer, C.J., 1997. Bringing water markets down to earth: the political economy of water rights in Chile, 1976–95. World Dev. 25 (5), 639–656.
Bevis, L., Barrett, C., 2020. Close to the edge: high productivity at plot peripheries and the inverse size-productivity relationship. J. Dev. Econ. 143, 102377.
Bhattarai, M., Narayanamoorthy, A., 2003. Impact of irrigation on rural poverty in India: an aggregate panel-data analysis. Water Policy 5 (5–6), 443–458.
Birner, R., Gupta, S., Sharma, N., 2011. The Political Economy of Agricultural Policy Reform in India: Fertilizers and Electricity for Irrigation. IFPRI Research Monograph, International Food Policy Research Institute, Washington, DC.
Boland, J. Whittington, D. 2000. Water tariff design in developing countries: Disadvantages of increasing block tariffs and advantages of uniform price with rebate designs. IDRC Research Paper.
Bos, M.G., Nugteren, J., 1974. On Irrigation Efficiencies, first ed. International Institute

for Land Reclamation and Improvement, Wageningen, The Netherlands, pp. 95.
Bos, M.G., Nugteren, J., 1982. On Irrigation Efficiencies, third ed. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, pp. 142.
Buisson, M.-C., Balasubramanya, S., 2019. The effect of irrigation service delivery and training in agronomy on crop choice in Tajikistan. Land Use Policy 81, 175–184.
Burney, J., Naylor, R., 2012. Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. World Dev. 40 (1), 110–123.
Burney, J.A., Naylor, R.L., Postel, S.L., 2013. The case for distributed irrigation as a development priority in sub-Saharan Africa. Proc. Natl. Acad. Sci. 110 (31), 12513–12517.
Carey, J.M., Sunding, D.L., 2001. Emerging markets in water: a comparative institutional analysis of the Central Valley and Colorado-Big Thompson projects. Nat. Resour. J. 41, 283–328.
Carter, M., Cheng, L., Sarris, A., 2016. Where and how index insurance can boost the adoption of improved agricultural technologies. J. Dev. Econ. 118, 59–71.
Colby, B.G., 1990. Transactions costs and efficiency in western water allocation. Am. J. Agric. Econ. 72 (5), 1184–1192.
de Azevedo, L.G.T., Balter, A.M., 2005. Water pricing reforms: issues and challenges in implementation. Int. J. Water Resour. Dev. 21 (1), 19–29.
de Fraiture, C., Giordano, M., 2014. Small private irrigation: a thriving but overlooked sector. Agric. Water Manag. 131, 167–174.
Deininger, K., 2003. Land Policies for Growth and Poverty Reduction: A World Bank Policy Research Report. Oxford University Press, New York, NY.
Desiere, S., Jolliffe, D., 2017. Land productivity and plot size: Is measurement error driving the inverse relationship? J. Dev. Econ. 130, 84–98.
Dillon, Andrew, 2011. The effect of irrigation on poverty reduction, asset accumulation, and informal insurance: evidence from northern mali. World Dev. 39 (12), 2165–2175.
Dinar, A., Mody, J., 2004. Irrigation water management policies: allocation and pricing principles and implementation experience. Nat. Resour. Forum 28, 112–122.
Dinar, A., Subramanian, A., 1998. Policy implications from water pricing experiences in various countries. Water Policy 1, 239–250.
Dinar, A., Zilberman, D., 1991. The economics of resource-conservation, pollution-reduction technology selection: the case of irrigation water. Resour. Energy 13, 323–348.
Domènech, L., 2015. Improving irrigation access to combat food insecurity and undernutrition: a review. Global Food Security 6, 24–33.
Donaldson, D, Storeygard, A, 2016. The view from above: Applications of satellite data in economics. Journal of Economic Perspectives 30 (4), 171–198.
Dreschel, P., Evans, A., 2010. Wastewater use in irrigated agriculture. Irrigat. Drainage Syst. 24 (1–2), 1–3.
Duflo, E, Kremer, M, Robinson, J, 2011. Nudging farmers to use fertilizer: Theory and experimental evidence from Kenya. American Economic Review 101, 2350–2390.
ECONADPT, 2015. The costs and benefits of adaptation: Results from the ECONADAPT Project. Watkiss, P. (Ed). ECONADAPT consortium. Available at: https://www.eco-logic.eu/sites/files/publication/2015/econadapt-policy-report-on-costs-and-benefits-of-adaptaiton-july-draft-2015.pdf.
Evans, A., Mateo-Sagasta, J., Qadir, M., Boeler, E., Ippolito, A., 2019. Agricultural water pollution: key knowledge gaps and research needs. Curr. Opin. Environ. Sustain. 36, 20–27.
Feijoó, M., Calvo, E., Albiac, J., 2000. Economic and environmental policy analysis of the Flumen-Los Monegros irrigation system in Huesca, Spain. Geograph. Anal. 23, 5–41.
Garrick, D., Aylward, B., 2012. Transaction costs and institutional performance in market-based environmental water allocation. Land Econ. 83 (2), 535–560.
Garrick, D., Whitten, S.A., Coggan, A., 2013. Understanding the evolution and performance of water markets and allocation policy: a transaction costs analysis framework. Ecol. Econ. 88, 195–205.
Gebregziabher, G., Namara, R., Holden, S., 2009. Poverty reduction with irrigation investment: an empirical case study from Tigray, Ethiopia. Agric. Water Manage. 96 (12), 1837–1843.
Giordano, M., Turral, H., Scheierling, S., Treguer, D., McCornick, 2017. Beyond "more crop per drop": Evolving Thinking on Agricultural Water Productivity. Colombo, Sri Lanka: International Water Management Institute (IWMI). (IWMI Research Report 169).
Global Commission on Adaptation. 2019. Adapt Now: A Global Call for Leadership on Climate Resilience. Global Center on Adaptation, Rotterdam, and World Resources Institute, Washington, DC.
Gómez-Limón, J., Berbel, J., 1999. Multicriteria analysis of derived water demand functions: a Spanish case study. Agric. Syst. 63, 49–71.
Gómez-Limón, J., Riesgo, L., 2004. Water pricing: analysis of differential impacts on heterogeneous farmers. Water Resour. Res. 40, W07S05.
Gourlay, S., Kilic, T., Lobell, D., 2017. Could the debate be over? Errors in farmer-reported production and their implications for the inverse scale-productivity relationship in Uganda. Policy Research Working Paper; No. 8192. World Bank, Washington, DC.
Grafton, R.Q., Libecap, G., McGlennon, S., Landry, C., O'Brien, B., 2011. An integrated assessment of water markets: a cross-country comparison. Rev. Environ. Econ. Policy 5 (2), 219–239.
Grafton, R.Q., Libecap, G.D., Edwards, E.C., O'Brien, R.J., Landry, C., 2012. Comparative assessment of water markets: insights from the murray—darling basin of Australia and the Western USA. Water Policy 14, 175–193.
Gross, A., Azulai, N., Oron, G., Ronen, Z., Arnold, M., Nejidat, A., 2005. Environmental impact and health risks associated with greywater irrigation: a case study. Water Sci. Technol. 52, 161–169.
Hanna, S., 2003. Transition in the American fishing commons: Management problems and institutional design challenges. In: Dolsak, N., Ostrom, E. (Eds.), The Commons in the New Millennium: Challenges and Adaptations. MIT Press, Cambridge, MA.
Hansen, V.E., 1960. New concepts in irrigation efficiency. Trans. ASAE 3 (1) 55–57, 61, 64.
He, T., Gao, F., Liang, S., Peng, Y., 2019. Mapping climatological bare soil albedos over the contiguous United States using MODIS data. Rem. Sens. 11, 666.
Hoanh, C.T., Johnston, R., Smakhtin, V., 2015. Climate change and agricultural development: a challenge for water management. In: Hoanh, C.T., Johnston, R., Smakhtin, V. (Eds.), Climate Change and Agricultural Water Management in Developing Countries. Wallingford, UK: CABI. pp. 1–10. (CABI Climate Change Series 8).
Hoogesteger, J., Wester, P., 2017. Regulating groundwater use: the challenges of policy implementation in Guanajuato, Central Mexico. Environ. Sci. Policy 77, 107–113.
Huang, Q., Dawe, E., Huang, J., Rozelle, S., Wang, J., 2005. Irrigation, poverty and inequality in rural China. Aust. J. Agric. Resour. Econ. 49 (2), 159–175.
Huang, Q., Rozelle, S., Lohmar, B., Huang, J., Wang, J., 2006. Irrigation, agricultural performance and poverty reduction in China. Food Policy 31 (1), 30–52.
Hussain, I., Hanjra, M., 2004. Irrigation and poverty alleviation: review of the empirical evidence. Irrig. Drain. 53 (1), 1–15.
Iglesias, E., Blanco, M., 2008. New directions in water resources management: the role of water pricing policies. Water Resour. Res. 44, W06417.
Injumba, J.N., Shenton, F.C., Clarke, S.E., Mosha, F.W., Lindsay, S.W., 2002. Irrigated crop production is associated with less malaria than traditional agricultural practices in Tanzania. Trans. Roy. Soc. Trop. Med. Hygiene 96, 476–480.
Israelsen, O.W., 1950. Irrigation Principles and Practices, vol. 471. John Wiley and Sons, Inc.: New York; pp. 497.
IWMI, 2004. 10 years of IWMI research – an overview. In: IWMI Annual Report. International Water Management Institute, Colombo, Sri Lanka, pp. 2004–2005.
Jacoby, H., 2017. "Well-fare" Economics of groundwater in South Asia. World Bank Res. Observer 32 (1), 1–18.
Janakarajan, S., Moench, M., 2006. Are wells a potential threat to farmers' well-being? Case of deteriorating groundwater irrigation in Tamil Nadu. Econ. Polit. Weekly 41 (37), 3977–3987.
Jensen, M.E., 1967. Evaluating irrigation efficiency. J. Irrigat. Drain. Div. Am. Soc. Civil Eng. 93 (IR1), 83–98.
Jensen ME. 1993. Impacts of irrigation and drainage on the environment. 5th N.D. Gulhati Lecture, The Hague, The Netherlands, 8 September, French and English; 26 pp.
Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T., Mwakalila, S.S., 2014. Freshwater resources. In: Field, C.B., Barros, V.R., Dokken, D. J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229–269.
Johansson, R.C., Tsur, J., Roe, T.L., Doukkali, R., Dinar, A., 2002. Pricing irrigation water: a review of theory and practice. Water Policy 4, 173–199.
Keiser, J., de Castro, M.C., Maltese, M.F., Bos, R., Tanner, M., Singer, B., Utzinger, J., 2005. Effect of irrigation and large dams on the burden of malaria on a global and regional scale. Am. J. Trop. Med. Hyg. 72, 392–406.
Keller, A., Keller, J., 1995. Effective efficiency: a water use concept for allocating freshwater resources. Water Resources and Irrigation Division Discussion Paper 22. Winrock International, Arlington, VA, USA.
Kibert, S., Alemu, Y., Boelee, E., Tekle, H., Alemu, D., Petros, B., 2010. The impact of a small-scale irrigation scheme on malaria transmission in Ziway area, Central Ethiopia. Trop. Med. Int. Health 15, 41–50.
Kibert, S., Lautze, J., McCartney, M., Nhamo, L., Yan, G., 2019. Malaria around large dams in Africa: effect of environmental and transmission endemicity factors. Malar. J. 18, 303.
Klaiber, H.A., Smith, V. K., Kaminsky, M., Strong, A. 2010. Estimating the Price Elasticity of Demand for Water with Quasi Experimental Methods. 2010 Annual Meeting, July 25–27, 2010, Denver, Colorado 61039, Agricultural and Applied Economics Association.
Lai, W., 2017. Pesticide use and health outcomes: evidence from agricultural water pollution in China. J. Environ. Econ. Manage. 86, 93–120.
Lefore, N., Giordano, M., Ringler, C., Barron, J., 2019. Sustainable and equitable growth in farmer-led irrigation in Sub-Saharan Africa: what will it take? Water Altern. 12 (1), 156–168.
Lewis, D., Zheng, H., 2019. How could water markets like Australia's work in China? Int. J. Water Resour. Dev. 35 (4), 638–658.
Liu, Y, Engel, B, Flanagan, D, Gitau, M, McMillan, S, Chaubey, I, 2017. A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. Science of the Total Environment 601–602, 580–593.
Lund, J.R., 1993. Transaction risk versus transaction costs in water transfers. Water Resour. Res. 29 (9), 3103–3107.
Luo, Q., Bellotti, W., Williams, M., Wang, E., 2009. Adaptation to climate change of wheat growing in South Australia: analysis of management and breeding strategies. Agric. Ecosyst. Environ. 129, 261–267.
Malchi, T., Maor, Y., Tadmor, G., Shenker, M., Chefetz, B., 2014. Irrigation of root vegetables with treated wastewater: evaluating uptake of pharmaceuticals and the associated human health risks. Environ. Sci. Technol. 48, 9325–9333.
Marshall, G., 2005. Economics for Collaborative Environmental Management: Regenerating the Commons. Earthscan, London.
Massarutto, A., 2002. Irrigation water demand in Europe. The impact of Agenda 2000 and the water framework directive. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.197.409&rep=rep1&type=pdf.

Mateo-Sagasta, J., Zadeh, S.M., Turral, H., (Eds.), 2018. More people, more food, worse water? Water pollution from agriculture: A global review. CGIAR Research Program on Water, Land and Ecosystems (WLE). Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; and International Water Management Institute (IWMI) Colombo, Sri Lanka.
McCann, L., Easter, K.W., 2004. A framework for estimating the transaction costs of alternative mechanisms for water exchange and allocation. Water Resour. Res. 40, W09S09.
Meinzen-Dick, R., 2014. Property rights and sustainable irrigation: a developing country perspective. Agric. Water Manag. 145, 23–31.
Mejias, P., Varela-Ortega, C., Flichman, G., 2004. Integrating agricultural policies and water policies under supply and climate uncertainty. Water Resour. Res. 40, W07S03.
Mekonnen, D., Choufani, J., Bryan, E., Abizari, A., Ringler, C., Amikuzuno, J., 2019. Irrigation-Nutrition Linkages: Evidence from Northern Ghana. IFPRI Discussion Paper 01887. International Food Policy Research Institute, Washington, DC.
Michelsen, A.M., Young, R., 1993. Optioning agricultural water rights for urban water supplies during drought. Am. J. Agric. Econ. 75, 1010–1020.
Molden, D., 1997. Accounting for Water Use and Productivity. IWMI/SWIM Paper No. 1. International Water Management Institute, Colombo, Sri Lanka, pp. 25.
Molle, F., 2004. Defining water rights: by prescription or negotiation? Water Policy 6, 207–227.
Molle, F., 2009. Water scarcity, prices and quotas: a review of evidence on irrigation volumetric pricing. Irrigat. Drainage Syst. 23, 43–58.
Molle, F., Closas, A., 2016. Groundwater Governance: A Synthesis. IWMI Project Report No. 6, Groundwater Governance in the Arab World. International Water Management Institute, Colombo, Sri Lanka.
Mukherji, A., Shah, T., Banerjee, P., 2012. Kick-starting a second green revolution in Bengal. Econ. Polit. Weekly 47 (18), 27–30.
Nakawuka, P., Langan, S., Schmitter, P., Barron, J., 2018. A review of trends, constraints and opportunities of smallholder irrigation in east Africa. Glob. Food Security 17, 196–212.
Namara, R., Hope, L., Sarpong, E.O., de Fraiture, C., Owusu, D., 2014. Adoption patterns and constraints pertaining to small-scale water lifting technologies in Ghana. Agric. Water Manag. 131, 194–203.
Nauges, C., Whittington, D., 2017. Evaluating the performance of alternative municipal water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and cost recovery. World Dev. 91, 125–143.
Olivera-Guerra, L., Merlin, O., Er-Rakib, S., 2020. Irrigation retrieval from Landsat optical/thermal data integrated into a crop water balance model: a case study over winter wheat fields in a semi-arid region. Rem. Sens. Environ. 239 (111627), 1–18.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, New York.
Ostrom, E., 2003. How types of goods and property rights jointly affect collective action. J. Theor. Polit. 15 (3), 239–270.
Pandey, V.L., Dev, S.M., Jayachandran, U., 2016. Impact of agricultural interventions on the nutritional status in South Asia: a review. Food Policy 61, 28–40.
Passarelli, S., Mekonnen, D., Bryan, E., Ringler, C., 2018. Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. Food Security 10, 981–997.
Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrig. Drain. 56, 367–378.
Perry, C.J., 2001. Charging for irrigation water: the issues and options, with a case study from Iran. Colombo, Sri Lanka: International Water Management Institute (IWMI). v, 17p. (IWMI Research Report 052).
Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T., Fang, J., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51.
Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533.
Rahman, A.A., Hasegawa, H., 2011. High levels of inorganic arsenic in rice in areas where arsenic-contaminated water is used for irrigation and cooking. Sci. Total Environ. 409, 4645–4655.
Rijsberman, F.R., Molden, D.J., 2001. Balancing water uses: Water for food and water for nature. Thematic background papers, International Conference on Freshwater, Bonn.
Ringler, C., Choufani, J., Chase, C., McCartney, M., Mateo-Sagasta, J., Mekonnen, D., Dickens, C., 2018. Meeting the nutrition and water targets of the Sustainable Development Goals: achieving progress through linked interventions. CGIAR Research Program on Water, Land and Ecosystems (WLE), International Water Management Institute (IWMI), Colombo, Sri Lanka.
Rogers, P., Bhatia, R., Huber, H., 1998. Water as a Social and Economic Good: How to Put the Principle into Practice. Global Water Partnership Technical Advisory Committee (TAC) Background Paper, No. 2.
Rohr, J.R., Civitello, D.J., Crumrine, P.W., Halstead, N.T., Miller, A.D., Schotthoefer, A.M., Stenoien, C., Johnson, L.B., Beasley, V.R., 2015. Predator diversity, intraguild predation, and indirect effects drive parasite transmission. Proc. Natl. Acad. Sci. 112 (10), 3008–3013.
Rohr, J.R., Barrett, C.B., Civitello, D.J., Craft, M.E., Delius, B., DeLeo, G.A., Hudson, P.J., Jouanard, N., Nguyen, K.H., Ostfeld, R.S., Remais, J.V., Riveau, G., Sokolow, S.H., Tilman, D., 2019. Emerging human infectious diseases and the links to global food production. Nat. Sustain. 2, 445–456.
Rose, C., 2002. Common property, regulatory property, and environmental protection: Comparing community-based management to tradable environmental allowances. In: Ostrom, E. (Ed.), The Drama of the Commons. National Academy Press, Washington, DC.
Rosegrant, M.W., Binswanger, H., 1994. Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation. World Dev. 22 (11), 1613–1625.
Rosegrant, M.W., Schleyer, R.G., 1996. Establishing tradable water rights: implementation of the Mexican water law. Irrigat. Drain. Syst. 00, 263–279.
Ruijs, A., Zimmermann, A., van den Berg, M., 2008. Demand and distributional effects of water pricing policies. Ecol. Econ. 66, 506–516.
Ruml, C.C., 2005. The Coase theorem and western U.S. appropriative water rights. Nat. Resour. J. 45 (1), 169–200.
Salman, A., Raddad, K., Shatanawi, M., Al Qudah, H., 2002. The economics of groundwater use in agriculture under different water prices and supply regimes in the upland area of Jordan. In: Hamdy, A., Lacirignola, C., Lamaddalena, N. (Eds.), Water Valuation and Cost Recovery Mechanisms in the Developing Countries of the Mediterranean Region. CIHEAM, Bari, pp. 177–190.
Schlager, E., 2007. Community management of groundwater. In: Giordano, M., Villholth, K. (Eds.), The Agricultural Groundwater Revolutions: Opportunities and Threats to Development. CABI Press, Cambridge, MA.
Schleyer, R.G., Rosegrant, M.W., 1996. Chilean Water Policy: the role of water rights, institutions and markets. Int. J. Water Resour. Dev. 12 (1), 33–48.
Schmitter, P., Kibret, K.S., Lefore, N., Barron, J., 2018. Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. Appl. Geogr. 94, 41–57.
Seckler, D. 1996. The new era of water resources management: From “dry” to “wet” water savings. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI). 20p. (IIMI Research Report 1).
Sheahan, M., Barrett, C.B., 2017. Ten striking facts about agricultural input use in Sub-Saharan Africa. Food Policy 67, 12–25.
Srinivasan, J.T., Reddy, V.R., 2009. Impact of irrigation water quality on human health: a case study in India. Ecol. Econ. 68, 2800–2807.
Steinmann, P., Keiser, J., Bos, R., Tanner, M., Utzinger, J., 2006. Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk. The Lancet 6, 411–425.
Teklu, B.M., Hailu, A., Weigant, D.A., Scholten, B.S., van den Brink, P.J., 2018. Impacts of nutrients and pesticides from small- and large-scale agriculture on the water quality of Lake Ziway, Ethiopia. Ecotoxicol. Trop. Reg. 25, 13207–13216.
Tsur, Y., 2000. Water regulation via pricing: the role of implementation costs and asymmetric information. In: Dinar, A. (Ed.), The Political Economy of Water Pricing Reforms. Oxford Univ. Press, New York, pp. 105–120.
Tsur, Y., 2005. Economic aspects of irrigation water pricing. Can. Water Resour. J. 30 (1), 31–46.
Tsur, Y., Dinar, A., 1997. On the relative efficiency of alternative methods for pricing irrigation water and their implementation. World Bank Econ. Rev. 11 (2), 243–262.
Tsur, Y., Dinar, A., Doukkali, R., Roe, T., 2004. Irrigation water pricing: policy implications based on international comparison. Environ. Dev. Econ. 6, 735–755.
Tsur, Y., Dinar, A., Doukkali, R.M., Roe, T.L., 2002. Efficiency and equity Implications of irrigation water pricing. Available at: http://web.worldbank.org/archive/website00662/WEB/PDF/TSUR_ET_.PDF.
UNEP, 2018: The Adaptation Gap Report 2018. United Nations Environment Programme (UNEP), Nairobi, Kenya. Available at: http://web.unep.org/ganadapt/publication/adaptation-gap-report-2018.
United Nations General Assembly. 2015. Transforming our world: the 2030 agenda for sustainable development. A/RES/70/1.
Uphoff, N., 1986. Improving International Irrigation Management with Farmer Participation: Getting the Process Right. Westview Press, Boulder, CO.
Uphoff, N., 1992. Local Institutions and Participation for Sustainable Development. International Institute for Environmental Development Gatekeeper Series, No. 31.
van Koppen, B., Moriarty, P., Boelee, E., 2006. Multiple-use water services to advance the millennium development goals. IWMI Research Report, No. 98. International Water Management Institute.
Varela-Ortega, C., Sumpsi, J.M., Garrido, A., Blanco, M., Iglesias, E., 1998. Water pricing policies, public decision-making and farmers’ response: implications for water policy. Agric. Econ. 19, 193–202.
Verchot, L.V., Noordwijk, M.V., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K.V., Palm, C., 2007. Climate change: linking adaptation and mitigation through agroforestry. Mitig. Adapt. Strat. Glob. Change 12, 901–918.
Vidal, A., Harrington, L.W., Fisher, M., 2014. Water scarcity and abundance, water productivity and their relation to poverty. In: Harrington, L.W., Fisher, M. (Eds.), Water Scarcity, Livelihoods and Food Security: Research and Innovation for Development. Routledge Press, New York.
Villholth, K.G., Sood, A., Liyanage, N., Zhu, T., Wada, Y., 2016. Global food production share from sustainable and unsustainable groundwater use. In: The 43rd International Association of Hydrogeologists Congress “Groundwater and society: 60 years of IAH,” Montpellier, France.
Wasserman, G.A., Liu, X., Parvez, F., Ahsan, H., Factor-Litvak, P., van Geen, A., Slavkovich, V., LoIacono, N.J., Cheng, Z., Hussain, I., Momotaj, H., Graziano, J.H., 2004. Water arsenic exposure and children's intellectual function in Araihazar, Bangladesh. Environ. Health Perspect. 112 (13), 1329–1333.
Wichelns, D., 2014. Do estimates of water productivity enhance understanding of farm-level water management? Water (Switzerland) 6 (4), 778–795.
Wichelns, D., 2015. Water productivity and water footprints are not helpful in determining optimal water allocations or efficient management strategies. Water Int. 40

(7), 1059–1070.
Willardson, L.S., Allen, R.G., Frederiksen, H., 1994. Eliminating Irrigation Efficiencies. In: USCID 13th Technical Conference, Denver, Colo., 19–22 October, 15pp.
Willardson, L.S., Allen, R.G., 1998. Definitive basin water management. In: Burns, J.I., Anderson, S.S. (Eds.), Proceedings, 14th Tech. Conf. on Irrig., Drainage and Flood Control, USCID, 3–6 June 1998, Phoenix, Ariz., pp. 117–126.
World Bank, 2016. 'High and Dry: Climate Change, Water, and the Economy'. The World Bank, Washington, DC. Available at: http://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy.
World Bank, 2017. Green Bond Impact Report. Working Paper 126764, The World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/343311520466168445/Green-Bond-Impact-Report-2017.
World Bank. 2019. (Accessed 15 November 2019).
World Water Assessment Programme (WWAP), 2017. The United Nations World Water Development Report, Wastewater: The Untapped Resource. UNESCO, Paris.
Worqlul, A., Jeong, J., Dile, Y., Osorio, J., Schmitter, P., Gerik, T., Srinivasan, R., Clark, N., 2017. Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Appl. Geogr. 85, 1–13.
Xie, H., Ringler, C., 2017. Agricultural nutrient loadings to the freshwater environment: the role of climate change and socioeconomic change. Environ. Res. Lett. 12, 104008.
Yang, Q.W., Lan, C.Y., Wang, H.B., Zhuang, P., Shu, W.S., 2006. Cadmium in soil–rice system and health risk associated with the use of untreated mining wastewater for irrigation in Lechang, China. Agric. Water Manag. 84, 147–152.
Yapi, Y.G., Briet, O.J.T., Diabate, S., Vounatsou, P., Akodo, E., Tanner, M., Teuscher, T., 2005. Rice irrigation and schistosomiasis in savannah and forest areas of Côte d'Ivoire. Acta Trop. 93, 201–211.
You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun, Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 36, 770–782.
Young, M.D., McColl, J.C., 2009. Double trouble: the importance of accounting for and defining water entitlements consistent with hydrological realities. Aust. J. Agric. Resour. Econ. 53, 19–35.
Zwarteveen, M., 1997. Water: from basic need to community: a discussion on gender and water rights in the context of irrigation. World Dev. 25 (8), 1335–1349.
Zwarteveen, M., Meinzen-Dick, R., 2001. Gender and property rights in the commons: examples of water rights in South Asia. Agric. Hum. Values 18, 11–25.