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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<sup>1</sup> 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

<sup>1</sup> 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<sup>2</sup> 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

<sup>2</sup> Development economics focuses on many topics beyond agriculture, where water may be a unit of inquiry, but this article only focuses on agriculture.

water-agriculture link (returns to agriculture under alternative water management regimes).<sup>3</sup>

### 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<sup>4</sup>), 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<sup>5</sup> (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

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

<sup>4</sup> 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.

<sup>5</sup> 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; Feijó 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; Zwartveen, 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; Zwartveen, 1997; Zwartveen 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.<sup>6</sup> 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

<sup>6</sup> These difficulties also hinder the setting of water prices and the allocation of water use rights.

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.<sup>7</sup> In addition, actual ET rates depend not only on

<sup>7</sup> 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.<sup>8</sup> 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<sup>9</sup> 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

(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.

<sup>8</sup> 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.

<sup>9</sup> 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>).

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<sup>10</sup>, 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 Clossas, 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

<sup>10</sup> 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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