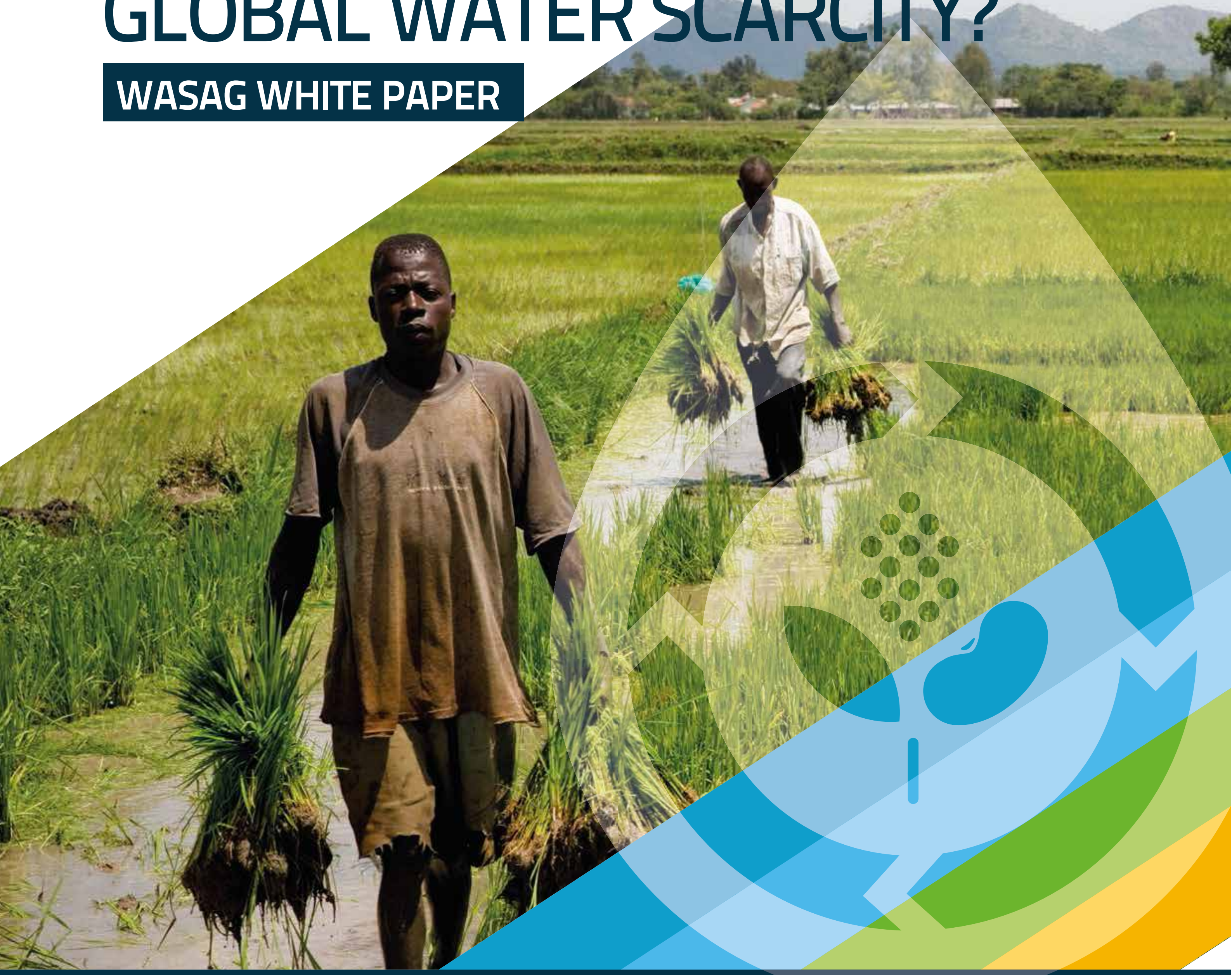
Food and Agriculture Organization of the United Nations

International Water Management Institute

WASAG | The Global Framework on Water Scarcity in Agriculture

CAN WATER PRODUCTIVITY IMPROVEMENTS SAVE US FROM GLOBAL WATER SCARCITY?

WASAG WHITE PAPER



WASAG WORKING GROUP ON
SUSTAINABLE AGRICULTURAL WATER USE

Can water productivity improvements save us from global water scarcity?

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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Foreword

The Global Framework on Water Scarcity in Agriculture (WASAG: www.fao.org/land-water/overview/wasag/en/) was established in 2016 and aims to bring together key players across the globe and across sectors to tackle the collective challenge of using water better in agriculture to ensure food security for all. It is an initiative for partners from all fields and backgrounds to collaborate in supporting countries and stakeholders in their commitments and plans related to the 2030 Sustainable Development Agenda, the Paris Climate Agreement (including implementing nationally determined contributions) and other plans and programs related to agriculture and water.

The working group on **Sustainable Agriculture Water Use** focuses on supporting the implementation of the Call for Action of 83 Ministers of Agriculture (as stated during the 9th Berlin Agriculture Ministers' Conference at the Global Forum for Food and Agriculture (GFFA) in January 2017) to address water scarcity risks in agriculture. It aims to increase awareness and action by agriculture and related ministries for more sustainable agricultural water use to address water scarcity for enhanced food security and nutrition, as well as for achieving all other Sustainable Development Goals.

This paper was prepared by Winston Yu wyu@worldbank.org, Stefan Uhlenbrook s.uhlenbrook@cgiar.org, Rachel von Gnechten r.vongnechten@cgiar.org, and Julie van der Bliek j.vanderbliek@cgiar.org from the International Water Management Institute (IWMI) and synthesizes discussions held at a WASAG workshop co-hosted by the International Center for Advanced Mediterranean Agronomic Studies (CIHEAM) and the CGIAR coordinated research program on Water, Land and Ecosystems (WLE) titled **"Can Water Productivity Improvements Save Us from Global Water Scarcity?"**, on 25-26 February at CIHEAM Bari in Valenzano, Italy. This paper received valuable inputs from Nicola Lamaddalena (CIHEAM Bari), C. Dionisio Pérez Blanco (Universidad de Salamanca), Chris Perry (independent consultant), Ranu Sinha (Global Water Partnership, GWP), Quentin Grafton (Australian National University), Thomas Anken (Agroscope, Switzerland), Julienne Roux (GWP), Hamil Emre Kislioglu (Ministry of Agriculture and Forestry, Turkey), Ruhiza Jean Boroto (Food and Agriculture Organization of the United Nations, FAO), Stefan Strohmeier (International Center for Agricultural Research in the Dry Areas, ICARDA), Mesfin Mekonnen (Daugherty Water for Food Global Institute at the University of Nebraska), Raffaella Zucaro (Government of Italy), Claudia Ringler (International Food Policy Research Institute, IFPRI), Petra Schmitter (IWMI), Soumya Balasubramanya (IWMI), Laura Sommer (Government of Switzerland), Graham Jewitt (IHE Delft), Poolad Karimi (IHE Delft), and Marloes Mul (IHE Delft). Additional feedback was received by participants of a FAO webinar on the paper held on 14 July 2020. This paper was edited for publication by Antoine Asselin-

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This paper is intended for a broad range of actors working on agriculture water use. This includes policymakers and decision-makers who are designing national or basin scale interventions to address water scarcity and stakeholders who would be impacted by these programs. This paper aims to provide some guiding recommendations to ensure more resilient and sustainable agricultural water use.

Executive summary

Agriculture is essential to achieving food security and supporting livelihoods and economies. Population increase, unsustainable production and consumption patterns, and climate change are critical drivers for increasing water stress. Urgent responses are required to improve agriculture water management, well integrated with other competitive sectors, particularly in water scarce regions. Sustainable water management is indispensable for climate-resilient growth and environmental integrity – unsustainable water management has devastating effects for people, economies and the environment. While agriculture is responsible for about 70 percent of global water withdrawals, agriculture will be an important part of the solution to solving the global water scarcity challenge. Getting agriculture water use right is essential to growing food in a more sustainable and resilient manner.

1. MONITOR AND ASSESS – DEVELOP WATER ACCOUNTS AND CONSIDER IMPACTS OF FUTURE CHANGES AND NATURAL VARIABILITY

Fully understanding the current state of water resources, including identifying where key uncertainties exist, will enable well-informed planning and management, and increase transparency in decision making. Quantifying water accounts at multiple scales allows policymakers to understand the limits of sustainable water use. Information on return flows from agricultural water use is particularly relevant to identifying how policies and interventions may lead to third party impacts. This requires sustained investments in monitoring across a wide range of hydrologic and meteorological parameters.

2. SET CONSUMPTION LIMITS – IDENTIFY SUSTAINABLE BOUNDARIES FOR CURRENT AND FUTURE WATER USE AT THE BASIN SCALE AND SET APPROPRIATE ALLOCATIONS FOR AGRICULTURE

Water resources can be exhaustible and non-renewable at different spatial and temporal scales. As such, water must be managed at an appropriate scale and within an identified sustainable boundary. Boundaries should be set in terms of maximum water consumption (instead of withdrawals) to prevent over-allocation and unintended negative impacts. Once these physical boundaries are defined, allocations (and reallocations) across various water-using sectors can be set and need to be supported and enforced by an effective regulatory and governance framework. The greatest allocations will in many basins in most countries go to agricultural water given the important role the agriculture sector plays in food security, employment, and in reducing poverty, hunger, and malnutrition.

3. THINK SYSTEMS – DESIGN AND IMPLEMENT AGRICULTURAL WATER USE INTERVENTIONS WITH THE WIDER SYSTEM CONTEXT IN MIND

Interventions on the farm often have impacts, interact, and are influenced by dynamics beyond the field. Thus, recognition and understanding of both broad natural systems and human systems (e.g. food, energy, social) is essential to minimizing unintended consequences and to maximize synergies. In practice, this requires a high degree of coordination and collaboration across traditional administrative divisions.

4. MANAGE TRADEOFFS – USE MULTIPLE POLICY INSTRUMENTS TO ACHIEVE MULTIPLE OBJECTIVES

There will be many objectives to achieve (e.g. conserve water resources, increase agricultural production or farmer's incomes). Some objectives may be complementary and have co-benefits, while others may be in conflict. Thus, tradeoffs will be inevitable and will need to be better understood and properly managed. Under these conditions, each policy objective should have its own instrument and embedded in a coherent broad policy framework that supports water, energy, food and environmental security objectives of governments.

5. MAXIMIZE AND SHARE BENEFITS FROM AGRICULTURE – SET TARGETS FOR AGRICULTURAL WATER USE THAT MAXIMIZE THE BENEFITS FROM THE SECTOR AND ENSURE THAT FARMERS AND VULNERABLE POPULATIONS CAN THRIVE

Depending on the goals of government for the agriculture sector, policymakers will need to determine how benefits can be maximized for farming communities. That is, how can the available water for the agriculture sector (set to allow environmental sustainability and future economic development) achieve the most for society. Governments should ensure that these benefits are shared with vulnerable populations (e.g. women, children, disabled).

6. EVALUATE, LEARN, AND COMMUNICATE – PUT IN PLACE ITERATIVE PROCESSES OF LEARNING TO BUILD PROGRESS TOWARDS MAXIMIZING BENEFITS FROM AGRICULTURAL WATER USE WITHIN SUSTAINABLE LIMITS

All water productivity interventions (policy or technical) are social experiments in practice. Since changes in human behavior are intended, anticipated outcomes are never certain. Thus, frequent evaluation is needed throughout implementation. Learning during actual implementation is inevitable and should be incorporated and communicated broadly early-on to create greater chances for success.

Introduction

The important role that the agricultural sector (here defined to include livestock) plays in eradicating poverty, hunger, malnutrition, particularly in rural areas where most of the global poor live, is well established (FAO, 2017). Unfortunately, the numbers of undernourished people are on the rise as progress towards globally set hunger targets is far too slow (FAO **et al.**, 2019). Furthermore, food security is strongly susceptible to global systemic shocks (as seen during the financial crisis of the late 2000s and currently with the COVID-19 crisis), making apparent the need to increase the resilience of the sector. Achieving the associated Sustainable Development Goals (SDGs) targets[1] by 2030 will require significant investments in increasing farmers' productivity and income and improving the sustainability and resilience of the sector (e.g., climate smart and profitable innovations; Jat **et al.**, 2020). This is in tandem with non-agriculture interventions such as investing in rural non-farm economies and the expansion of social development programs and other public services in rural areas. Water resource constraints, both existing and emerging, threaten to undermine gains made.

According to the United Nations (2018), over 2 billion people live in places experiencing high water stress. Numerous factors are contributing to increased global water scarcity (e.g. climate change, population growth, increasing urbanization, expanding industrial demands, changing diets). Some areas are already facing significant environmental and socio-economic impacts from the over-use of water for agricultural production. Under various future climate scenarios, the situation is expected to worsen in many areas (Gosling and Arnell, 2013; IPCC, 2018). This raises concerns whether there will be adequate water for all uses and users and particularly for food production, responsible for about 70 percent of global withdrawals (Giordano, 2007; Falkenmark, 2013; Perry **et al.**, 2017; Sadoff **et al.**, 2020). In response to this scarcity (both physical and economic[2], a wide variety of water productivity interventions (both technical and policy instruments) have been used in the sector.

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1 For instance: SDG 1: End poverty in all its form everywhere, SDG 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture and SDG 6: Ensure availability and sustainable management of water and sanitation for all. More details regarding these goals and specific targets and indicators can be found here: https://sustainabledevelopment.un.org/sdgs

2 Physical water scarcity occurs when there is not enough water to meet all demands. Arid regions are most often associated with physical water scarcity, but an alarming new trend is an artificially created physical water scarcity due to over allocation and overdevelopment of water resources. Symptoms of physical water scarcity include, among other factors, severe environmental degradation and increasing occurrence of conflicts. Economic water scarcity is caused by a lack of investment in water or human capacity to satisfy the demand for water, even in places where water is abundant. Symptoms of economic water scarcity include inadequate infrastructure development, people have trouble getting enough water for domestic and other purposes, high vulnerability to seasonal fluctuations, floods and droughts, and inequitable distribution of water, even when infrastructure exists (FAO, 2009).

Commonly, such interventions aim to produce more output for the same or less level of input at the plot level. This objective itself may be adequate. However, water productivity interventions can have multiple objectives apart from reducing the impacts of water scarcity. These interventions may be sought to, inter alia, raise farm-level income, alleviate poverty, increase crop diversification, and support water reallocation from agriculture to other sectors including the environment (Molden **et al.**, 2010; Giordano **et al.**, 2017). Moreover, different actors may have different intentions, perspectives, and scales of interest. Breeders, driven by scientific crop improvements, often focus on individual plant productivity enhancements. Farmers, needing to support livelihoods, focus at the farm-scale on maximizing incomes and food security for their immediate households. Public water resources managers, driven by long-term sustainability concerns, focus at the basin, national, or regional scales. Assessing the effectiveness of any water productivity intervention must start with understanding their defined objectives and the metrics considering the scale of the intervention.

To complicate matters, there are often inconsistencies, ambiguities, and misconceptions with water productivity terminology. This is important as it prevents actors from developing a shared understanding and vision of the issues at stake and of the objectives of the proposed interventions. Definitions have been developed from various academic fields each with different perspectives. For example, an engineer defines water "lost" when it flows beyond its system boundary, whereas a hydrologist sees this as not a "loss", but instead a "source" to an aquifer, wetland or for evaporation (Perry **et al.**, 2017). The terminology utilized can also be ambiguous. For example, "water use" is commonly said; however, the distinction between water "use" and water "consumption" is essential to the management of the total resource. Water productivity terms can also be misleading. For example, a common misperception is that water productivity interventions result in water "savings" at larger scales. Determining water "savings" is much more complex as it requires an understanding of the broader hydrological context and respective water accounts across scales (Grafton **et al.**, 2018).

Despite these challenges, are there common guiding principles to help policymakers and involved professionals to design interventions that minimize the impacts of water scarcity on food security, and vice versa? The aim of this paper is to summarize the experience with water productivity interventions observed in the field, to better understand the perspectives and scales of different actors, and to synthesize some key principles to follow. These recommendations will help policymakers and stakeholders more positively address the title of this paper.

1. Observations from the literature

There is ample evidence from the field that while water productivity interventions (broadly defined) are successful in achieving some objectives (e.g. improved farmer incomes), they may not be successful in others (e.g., conservation of water resources, environmental impacts). For example, policymakers often implement these interventions expecting water "savings" to be used by other users. The empirical evidence suggests otherwise. Pérez Blanco **et al.** (2019) reviewed over 240 water productivity intervention studies and found that "higher irrigation efficiency typically contributes to intensification of water scarcity through increased water consumption in the agricultural process." Similarly, a global review of the impact of hi-tech irrigation (here defined as any technical intervention designed to improve water delivery to the farmer) on available "savings" reveals inconclusive results, indicating that these interventions are often associated with an increase in water consumption, and relatively constant water productivity (i.e. per unit of water

consumed in production) (Perry **et al.**, 2017). Moreover, Wichelns (2015) argues that higher estimates of water productivity are not necessarily associated with higher yields, larger incomes, or larger amounts of production for sale or home consumption. As such, he argues that there is no economic rationale to maximizing water productivity.

Increases in water consumption are often a result of unanticipated expansion of crop production and/or shifts in cropping patterns including into more water intensive crops. For example, Ahmad **et al.** (2007) showed in the Punjab province of Pakistan that the introduction of resource conservation technologies (zero tilled crops and laser leveling) reduced water application at the field scale (24 to 32 percent) and increased farm incomes. However, overall water consumption in the basin increased by 59 MCM per year in part due to the associated expansion of cropped areas. Similarly, Scott **et al.** (2014) showed increases in irrigated area and crop diversification (from water-intensive cereals to high-value crops with lower water requirements e.g. vineyards, olives, fruit trees, vegetables) in the Guadiana Basin of Spain following government support in irrigation efficiency improvements. Overall consumptive use increased by over 200 MCM per year from 2002 to 2006.

Many water productivity interventions have also been introduced to tackle the worldwide concern over unsustainable groundwater use (Famiglietti, 2014). For example, in the State of Rajasthan in India, the government promoted drip irrigation with the objective of conserving groundwater and increasing resilience to climate change. Birkenholtz (2017) found that this program led to farmers intensifying production, shortening fallow times, and expanding production areas from 40 percent to 67 percent on average. In the State of Kansas in the United States of America, from 1998-2005 the government promoted the adoption of more efficient irrigation systems to reduce groundwater use. The State paid up to 75 percent of the cost of purchasing and installing new or upgraded irrigation technology. Pfeiffer and Lin (2014) found that this correlated with an increase in groundwater extraction, on average by 4 440 to 6 170 m^3 per field (average field size around 70 hectares). In the North China Plain, Kendy **et al.** (2003) found that the long-standing policy of promoting irrigation efficiency to curb over-extraction of groundwater resulted in a decrease in pumping rates (over 50 percent since the 1970s) but a continued decline in groundwater tables (almost 20 m over the same period) due to crop expansion.

Water productivity interventions can also have unintended consequences on environment flows and ecosystem services. Scott **et al.** (2014) showed that water productivity interventions (i.e. irrigation efficiency improvements, canal lining, and automated monitoring and control systems) in the Imperial Valley of California intended to generate “saved” water to be transferred to the city of San Diego reduced environmental flows to the Salton Sea (originally around 1.7 BCM). This contributed to its increased salinity. Carrillo-Guerrero et al. (2013) describe the importance of US irrigation return flows (on the Colorado River) to the downstream riparian ecosystems and delta wetlands in Mexico. Given that most environmental water supply is not

guaranteed, improvements in agricultural water use efficiency and reductions in canal seepage would reduce flows to these ecosystems. Similarly, Qureshi **et al.** (2010), using the Murray-Darling Basin in Australia as an example, argue that in cases where irrigation "losses" serve as substantial return flow for the environment, a policy of subsidizing investments in irrigation and conveyance system upgrades may not be beneficial considering the whole system. Irrigation expansion can also have negative impacts on biodiversity (e.g., Riedener **et al.**, 2013) leading to multiple repercussions.

To minimize increased consumption and the "rebound effect"[3] from efficiency and productivity interventions, the role of regulatory instruments is clear. Mekonnen **et al.** (2019, 2020) demonstrate that in Nebraska, United States, the observed shift to more efficient irrigation systems (e.g. changing from gravity to center pivot systems) and setting regulatory limits on pumping for irrigation has helped to reduce the field level irrigation application depth in three Natural Resources Districts (NRDs). These strict controls on abstraction levels and groundwater usage have helped to maintain overall consumption. Similarly, in the Guadalquivir river basin in Spain where significant efforts were made to transform old open-channel distribution systems into pressurized pipe networks to save an estimated 3 000 Mm^3 annually, Borrego-Marin and Berbel (2019) show that indeed withdrawals were reduced. Moreover, consumption remained constant due to the prohibition of irrigated area expansion (in effect since 2005) and the government retention of all 'water savings'.

How can these diverse observations and experiences be explained? What can be learned from these experiences moving forward to guide policymakers? The following sections disentangle some common challenges to achieving real water savings.

[3] Wheeler **et al.** (2020) use this term

2. Confusing terminology and multiple meanings

For professionals broadly working on water resources management and development, collaborating with different academic disciplines and perspectives is common (e.g. hydrology, water engineering, irrigation, economics, agronomy, ecology, behavioral sciences, law). Though this diversity of views has its strengths, it also brings a complicated mix of jargon and terminology. This multiplicity of terms poses a challenge in understanding the impacts of various interventions that fundamentally cross different disciplines and scales (e.g. Balasubramanya and Stifel, 2020). These inconsistencies can cause confusion and miscommunication for policy- and decision-makers, and researchers (those who evaluate the impacts) or even trigger conflicts.

For example, the distinction between water "use" (or abstraction or withdrawals i.e. water removed or diverted) and water "consumption" (amount depleted and no longer available in the reference system) is critical to managing the total resource (unlike other natural resources e.g. forests, land, minerals or fossil fuels).

Moreover, different technical communities view productivity differently. The term water productivity refers to the ratio of the net benefits (e.g. from crop, forestry, fishery, livestock) to the amount of water (whether consumed or withdrawn from a source) used to produce those benefits. In its broadest sense, it reflects the objective of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed (Molden **et al.**, 2010). The selection of the numerator and denominator depends on the scale of analysis and the interest of the actor. Productivity can be defined in physical terms (e.g. [kg/m^3]: ratio of agricultural output to the amount of water consumed – 'more crop per drop') or in economic terms (e.g. [USD/m^3]: value derived per unit of water used). Note that since this is a partial factor productivity metric, maximizing this metric may not be consistent with maximizing net returns for the farmer (Wichelns, 2015).

This contrasts with classical engineering terms for efficiency. Here, irrigation efficiency traditionally reflects the ratio of water consumed relative to the volume of irrigation water applied. Though this perspective is appropriate with respect to the planning, design, and operation of an irrigation system, this perspective tends to treat water leaving the boundary of this engineering system as a "loss". A hydrologist in contrast, might view this engineering efficiency "loss" as a source of important water for other parts of the hydrologic cycle (e.g. recharge to an aquifer, or base flow to a river). Thus, as Perry (2011) points out, the term "efficiency" carries the implication that the increase in efficiency actually "saves" some of the resource, which is often not the case (as described in the previous section).

The multi-disciplinary necessity to approaching water scarcity requires unambiguous productivity terminology. Policymakers must be clear in the terminology they use and understand the misconceptions of commonly used terms such as water "savings". From a public policy and societal perspective, the physical basin scale (notwithstanding often incongruity between surface and groundwater) is needed for analysis of interventions and to harmonize across multiple incentives and interests. To address the concerns around terminology, this calls for a common framework for accounting of the physical resource over space and time for which different water productivity interventions, across different disciplines and actors, can be evaluated.

3. Water accounting: tracking stocks and flows

In the field of hydrology, a water balance equation can be used to describe how much water flows in and out of a defined basin system. The principles of conservation of mass are used whereby any water entering the system (via precipitation or a transfer from another system), must be balanced with any water leaving the system either as evaporation or runoff (eventually leaving in the form of river or groundwater discharge), or stored in different hydrological storages (e.g. snow and ice, soil water, groundwater, vegetation or human systems; e.g. Uhlenbrook, 2006). Added to this, the different uses of water can also be defined. This results in physical water accounts, i.e., the stocks, flows, and uses of water throughout the system over time. Water accounting presents information in a standardized manner that is understandable across different disciplines and can be used to investigate different water resource decisions and

policies. Water accounting tools to systematically support quantitative assessments for management of water supply, demand, distribution and resource development are well developed in the literature (Steduto **et al.**, 2012; Karimi **et al.**, 2013a; UN, 2012). These have been applied in many countries (e.g. Pakistan[4], Iran[5], Vietnam[6]) and basins (e.g. Awash[7], Helmand[8] , Indus[9]).

As with all types of modeling tools, obtaining the required data, especially in developing countries, is not trivial. With declining public budgets devoted to maintaining hydro-meteorological systems, the ability to monitor key hydrological and meteorological parameters has increasingly become difficult. A World Bank (2018) review identified common obstacles to providing adequate and effective hydro-meteorological services, such as, insufficient budgets, inability to attract, train, and retain qualified staff, inadequate data management systems, insufficient integration between hydrological and meteorological services, poor connection with users. This is especially worrisome in the context of climate change and the (in)ability for governments to narrow the uncertainties around key hydrologic and climatologic processes. Moreover, even in the robust of networks and with ample funding, data can always be subject to bias and error (Wilby **et al.**, 2017). However, with improved field observation methods and more avenues to collect data (e.g. via drones, satellites and remote sensing, citizen science efforts), inter-linked systems (e.g. mobile phones, internet of things), and new ways to analyze and integrate (big) data (e.g., artificial intelligence, block chain), these traditional field-level systems can be supplemented to better quantify the basic water accounts. Indeed, society is in what the World Economic Forum calls the Fourth Industrial Revolution on Water[10] (WEF, 2018).

To predict the impacts of a water productivity intervention using the water accounting approach, at its simplest, all water used for any purpose within a defined system goes to one or more of the following categories (Perry, 2017) – see Figure 1:

1. **Consumptive use**
   a. Beneficial consumption (i.e. water evaporated or transpired for its intended purpose)
   b. Non-beneficial consumption (i.e. water evaporated or transpired not for its intended purpose)
2. **Non-consumptive use**
   a. Recoverable flows (i.e. water that can be captured and re-used)

4 Ahmad **et al.** (2007).

5 Delavar **et al.** (2020)

6 Dost **et al.** (2013); Karimi **et al.** (2015)

7 Dost **et al.** (2013); Karimi **et al.** (2015)

8 Peiser and Bastiaanssen (2015)

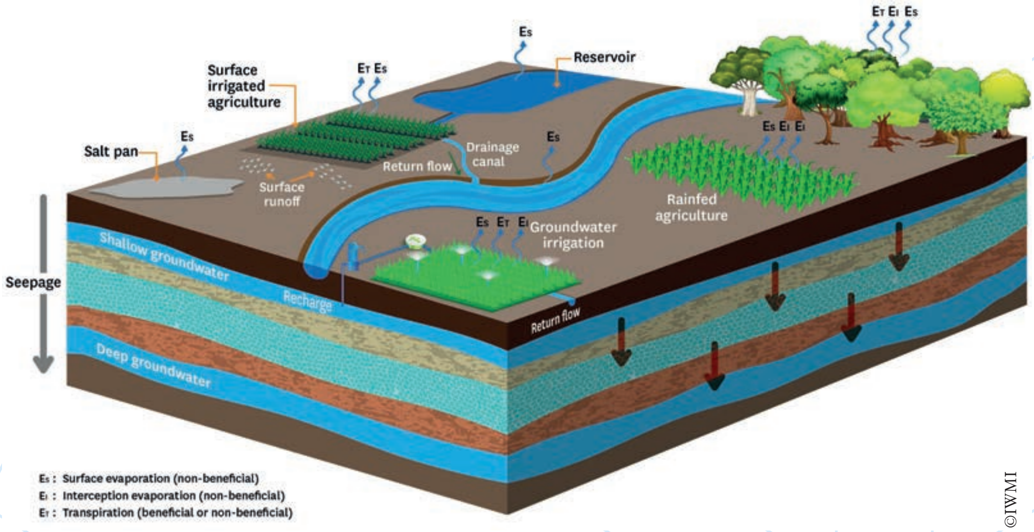
9 Karimi **et al.** (2013b)

10 The Fourth Industrial Revolution on Water envisions a major role for emergent technologies and their applications in solving many of society's challenges in the water sector. With technology becoming increasingly connected and a greater convergence amongst the digital, physical and biological realms, new opportunities are emerging to tackle the most pressing issues in water management.

   b. Non-recoverable flows (i.e. water that is truly lost and unavailable or of insufficient quality for intended use)

3. **Change in storage**

Figure 1. Note that the evaporation fluxes are synonymous with consumptive uses and may be beneficial (i.e. evaporated or transpired for its intended purpose) or non-beneficial (i.e. not evaporated or transpired for its intended purpose e.g. weeds, surface evaporation from the reservoir). To determine whether the non-consumptive uses (e.g. return flows, surface runoff) are recoverable or non-recoverable depends on their destination. The surface runoff into the salt pan (shown) would be non-recoverable. The recharge into groundwater would be recoverable. Real savings can mainly be achieved by reducing consumption (particularly non-beneficial uses if crop performance is unchanged) and reducing non-recoverable flows.



The law of conservation of mass dictates that the fractions at each category must sum to one. That is, all water that is applied for any purpose goes somewhere. Most attention is focused on the beneficial consumption; for example, transpiration from an irrigated or rain-fed crop or evaporation from a cooling tower at a thermal power plant. This contrasts with non-beneficial consumptive use that may not be directly related to the intended purpose; for example, evaporation from a reservoir, irrigation drain or unintended weeds. If these amounts can be converted into 'productive' uses, then gains will have been made. There are also non-consumed fractions that can either be re-used (for example return flows to drains, water used for hydropower purposes) or not (e.g. flows to saline groundwater sinks, flows to the sea). Note that water quality usually changes along its path preventing the resource from certain uses or requiring treatments (e.g. return flow from irrigated schemes may be polluted with agrochemicals). Reducing the amount of water that ends up in places that cannot be accessed for re-use (i.e. non-recoverable flows) would be a gain from the water management perspective. ***Understanding how the resource is partitioned amongst these different categories is the first step in better managing its sustainability.***

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4. Water productivity interventions: different actors, objectives and scales

A wide range of interventions are available to address water scarcity conditions. Many directly relate to improving water productivity; that is, producing more (whether in physical biomass or economic terms) for a given unit of resource utilization. For example, advances in crop science may lead to new breeds and varieties of crop that require less inputs per unit of output. Similarly, introducing different agronomic practices at the field (e.g. mulching, zero tillage, laser land leveling, alternating wetting and drying, deficit irrigation) may in the end require less applied water per unit output as non-beneficial evaporation is minimized. Irrigation engineers often employ a wide range of "modernization" interventions (e.g. canal lining, control structures,

participatory irrigation management) to improve the delivery efficiency and reliability of an irrigation system for farmers. High precision irrigation technologies (e.g. drip, sprinklers) may also result in farm-level delivery efficiencies, thereby benefiting the farmer not only in terms of reducing water costs (if farmers are charged and reduce deliveries) but also with respect to saving labor, precision application of fertilizers and chemicals, minimizing leaching of nitrates and other pollutants, and diversifying crops. Finally, economic instruments (e.g. pricing, water markets) and management and regulatory interventions (e.g. resource re-allocations, improved monitoring, strengthened governance arrangements, quotas and caps on irrigation, buybacks) may have positive impacts on water utilization and simultaneous productivity enhancements. The challenge with designing effective productivity interventions relate to the different objectives and incentives that different actors may have, and the complexity of systems and multiplicity of scales that these interventions take place in.

4.1 DIFFERENT ACTORS AND OBJECTIVES

Depending on the actor (e.g. farmer, basin manager, environment, government, household, private sector), reducing water scarcity itself may not be the key objective. Rather, people and communities may aim to maximize farm incomes and local food availability, the "environment" may aim to limit resource depletion and impacts on ecosystem service provision, and national governments may aim to stimulate effects on growth and jobs. As such, different actors may pursue a wide range of interventions some of which may not be directly water related (e.g. job training programs into other sectors, import of food, promote other industries with greater growth potential, social protection programs, environment conservation programs).

Moreover, water productivity interventions themselves may have different objectives (Giordano **et al.**, 2017). Is the water productivity intervention intended to increase agricultural production, reduce agricultural water consumption, increase farm-level income, alleviate poverty and inequity, or make more water available for downstream users? Public policymakers must, together with stakeholders, identify what they want to achieve broadly and how a water productivity intervention can support this, while also recognizing that different actors may have different objectives that may both conflict and be complementary with each other. Tradeoffs will be inevitable.

4.2 DIFFERENT SCALES

Impacts of changing or shifting water use are scale dependent. Every water productivity intervention will have an impact on some component of the water accounts. The critical question is the scale of the perspective to take when evaluating an intervention. For example, water productivity metrics can be used in different ways depending on the scale of interest, system boundaries, and the actor (see Table 1).

Table 1
Water productivity at different spatial scales

Scale	Crop	Field	Farm	Irrigation system	Basin	Region/ country
						
Purpose	Assessing energy conversion, biomass or harvestable yield from a crop or cultivar	Assessing biomass or harvestable yield from a cropping system	Assessing harvestable yield or economic return from a farm's crop production	Assessing irrigation system performance in terms of harvestable yield, water delivered, operation and maintenance, or economic return	Assessing water allocation, including use of water in agriculture compared to other sectors	Assessing water allocation to achieve food, water, energy etc. security at national or regional scales
Users	Plant physiologists, breeders, private sector	Soil scientists and crop agronomists, agricultural extension agents, farmers, private sector	Agronomists, farmers, private sector	Irrigation engineers, agronomists/ agriculture extension agents, water managers	Water managers at basin level, hydrologists, water users	Policy makers at country or regional levels, including environment, food and nutrition, water, energy, trade, etc.

From Giordano et al. (2017), adapted, last column added

Understanding these different scales matters because impacts of an intervention may occur at multiple spatial scales (intentional or otherwise). For example, modernized irrigation technologies are often branded for their water "saving" capabilities and improved irrigation "efficiencies." Many studies (see section above) reveal that water "savings" at the farmer-scale or irrigation system-scale may not translate to water "savings" for other actors within a larger basin scale. In fact, "advanced irrigation technologies that increase irrigation efficiency may even increase on-farm water consumption, groundwater extractions, and water consumption per hectare" (Grafton **et al.**, 2018). This lack of broader scale water "savings" is because, at the farm-scale, farmers tend to utilize the available resources for generating additional benefits which could result in the cultivation of more water-intensive crops, increase the cropping intensity, expand irrigated areas, or see "a strong marginal yield response from additional water" with the same crop (Grafton **et al.**, 2018). The authors refer to this as the **irrigation efficiency paradox**.[11] Moreover, national level policies and productivity interventions may have differential impacts on basins and sub-basins both within a country and in a transboundary context.

[11] This is analogous to Jevons paradox in economics whereby technological progress increases the efficiency with which a resource is used while simultaneously the rate of consumption of that resource rises due to increasing demand (e.g., more fuel-efficiency does not result in reduced fuel consumption, but in an overall increase).

5. Where do we go from here?

With many places now facing increasing water scarcity, policymakers are faced with difficult choices about how to limit excessive or unsustainable consumption of water resources. These choices are complex with sometimes multiple consequences for the reasons given above. Nonetheless, from the public policy perspective, decision making should be informed and guided by the following six principles:

5.1 MONITOR AND ASSESS: DEVELOP WATER ACCOUNTS AND CONSIDER IMPACTS OF FUTURE CHANGES AND NATURAL VARIABILITY

Fully understanding the current state of water resources (both quantity and quality, in space and time), including identifying where key uncertainties exist (e.g. future demand projections, groundwater contributions to river flow, future variability etc.) will enable well-informed planning and management, and increase transparency in decision

making. This is especially critical in the context of climate change and increased future water scarcity. Quantifying water accounts from farm to basin scales allows policymakers to better understand the sustainable limits of the water resource and forces them to negotiate priorities and interventions within that sustainable boundary.

Developing water accounts requires sustained investments (both capital and recurrent) in monitoring systems across a wide range of hydrologic and meteorological parameters (as discussed earlier) at multiple scales (e.g. field, farm, basin, national). This is not a trivial exercise in practice, especially at the field level. However, modern Earth observation and remote sensing products (of evaporation) in tandem with new big data approaches (e.g. internet of things, use of cellular network towers, citizen science efforts, artificial intelligence and machine learning approaches, drones) can complement traditional ground-based monitoring networks to provide the baseline knowledge needed to build water accounts at various scales.

With water accounts in place, the impact of future exogenous changes (e.g. climate, population, demographic shifts), drivers for water use, as well as various water productivity and policy interventions can be evaluated at the crop, field, farmer, basin and regional scales. Information on return flows from agricultural water use and whether they are beneficial or not (i.e. they flow to a sink) is particularly relevant to identify whether policies and interventions will lead to third party impacts. Especially from the public resource management and environmental perspectives, basin implications need to be considered. This can be particularly challenging in a transboundary context. Water accounting can help understand where locally "saved" water really goes. Water accounting tools can also help policymakers better foresee risks, tradeoffs, and/or unintended consequences and make more "transparent who gets what and where" (Grafton **et al.**, 2018).

5.2 SET CONSUMPTION LIMITS: IDENTIFY SUSTAINABLE BOUNDARIES FOR CURRENT AND FUTURE WATER USE AT THE BASIN SCALE AND SET APPROPRIATE ALLOCATIONS FOR AGRICULTURE

Water resources can be exhaustible and non-renewable at different spatial and temporal scales. As such, water must be managed at an appropriate scale and within an identified sustainable boundary to ensure adequate water for various current and future users (agriculture, industry, energy, domestic, environment, etc.). For example, such boundaries for basins are well established in the literature (Loucks 1997, 2000; Sandoval-Solis **et al.**, 2011; Wu **et al.**, 2015). Moreover, boundaries should be set in terms of maximum water consumption (instead of withdrawals which most water rights administration systems regulate) to prevent over-allocation and unintended negative impacts.

Once these physical boundaries are defined, allocations (and reallocations) across various water-using sectors can be set and guided by stakeholder consultations and supported and enforced by an effective regulatory and governance framework. Particularly in larger basins, limits will need to be set at sub-basin scales but coordinated at basin scales (O'Donnell **et al.**, 2019). These allocations and limits will require politically challenging choices given the nature of the tradeoffs to make and interests of various stakeholders (now and in the future). Limits should consider future conditions (e.g. climate change, development of various sectors), existing variability, and be regularly reviewed and adjusted as needed. Allocations themselves may be more dynamic and respond to short-term challenges (e.g. shocks) including buffering and sharing between physically defined watersheds. Nonetheless, in many basins in most countries the greatest allocations will go to agriculture water given the important role the agriculture sector plays in food security, employment, and in reducing poverty, hunger, and malnutrition. Moreover, with set consumption limits, policymakers can then evaluate various water productivity interventions and assess whether impacts (e.g. biophysical, economic, distributional) are acceptable. Perry **et al.** (2017) and others, for example, argue that water allocation limits based on water accounting must be done prior to promoting hi-tech irrigation technologies.

5.3 THINK SYSTEMS: DESIGN AND IMPLEMENT AGRICULTURAL WATER USE INTERVENTIONS WITH THE WIDER SYSTEM CONTEXT IN MIND

Interventions on the farm often have impacts, interact, and are influenced by dynamics beyond the field. Thus, recognition and understanding of broad natural systems (e.g. watershed, river basin, groundwater-surface water interconnections, source to sea) and their interactions with human systems (such as food, energy, and social systems) are essential to minimizing unintended consequences. This recognition of the importance of better understanding "hydrosociology" (Falkenmark, 1979) and contemporary permutations (e.g. Sivapalan **et al.**, 2011) is well established. In practice, this requires a high degree of coordination and collaboration across traditional administrative divisions.

Actions at an individual farm can have impacts on larger food systems and at the same time be impacted by them. For example, water productivity interventions that aim to shift the pattern of cropping towards higher value crops (i.e. more economic benefit per unit applied water) may impact local market prices; not only the price of the new crop by increasing supply, but also the price of the old crop by decreasing supply (assuming that markets are not distorted through price-based incentives, e.g., guaranteed prices etc.). This could have broader implications on the supply chain, both upstream (e.g. seeds and fertilizers) and downstream (e.g. agro-processing) for both the old and new crop. Conversely, these interventions may not succeed if not supported by the current or anticipated food system (e.g. availability of seed suppliers, required fertilizers, labor, knowledge of new cultivars, market access). For example, Burt **et al.** (2008) critique proposals by Cooley **et al.** (2008) to shift 25 percent of the irrigated field crops in

the Central Valley in California to higher-value irrigated vegetables to generate water savings of about 1.5 BCM. While Burt **et al.** (2008) acknowledge that vegetable crops may use less water than field crops, they argue that such a shift is unrealistic in practice because impacts on farmer incomes would be negative, especially given that the existing market could not absorb such a large increase in vegetable production.

Similarly, the nexus between agriculture and energy systems is well documented (Ringler **et al.**, 2013). Significant energy resources are needed to pump water for irrigation purposes and pressurize high-precision systems (e.g. drip and sprinkler systems). At the same time, water is needed to produce energy (e.g. cooling for thermal power plants) including the conversion of large areas of land for biofuel production (consuming in many cases more water than before; see for example Jewitt and Kunz, 2011). This can have significant impacts on the prices of basic crop commodities (Rosegrant, 2008; Diaz-Bonilla, 2013). Thus, well designed water productivity interventions may also need to consider energy systems. For example, recent research in India has examined the water impacts of using solar-powered irrigation in lieu of traditional fuels to support agriculture production (Verma **et al.**, 2018; Shah **et al.**, 2016; Gupta, 2019). Concerns over the impacts of this policy on groundwater over-extraction are well justified. In response, experiments are under way whereby farmers are given the option to sell energy to the grid ('solar power as a remunerative crop'). Reducing groundwater use depends on setting an appropriate electricity feed-in-tariff (Shah **et al.**, 2016). The feed-in-tariff must be high enough to dis-incentivize groundwater pumping (while maintaining or improving farm incomes), but at the same time not too high to discourage crop production (important for meeting local consumption needs).

Finally, ecosystem services provide benefits that are essential to human health and well-being (WLE, 2014). Healthy ecosystems can positively impact agriculture, for example, through soil nutrient cycling, regulation of water flows, carbon sequestration, pollination, and pest control (Zhang **et al.**, 2007). Beyond the agriculture sector, ecosystems can also provide water quality enhancement and flood protection. These benefits are not always physically well understood nor easy to economically value (Ruckelshaus **et al.**, 2015; Bagstad **et al.**, 2013; Holzman, 2012). An example of the interconnectedness of agriculture and ecosystem services can be seen in the Volta River Basin. Here, poor upstream catchment management is contributing to decreased storage capacity in the basin, impacting dry season irrigation and fish (WLE, 2014). Not surprising, there are many notable global examples of detrimental impacts on the environment of over-consumption of water in the agriculture sector (e.g. Aral Sea, Ogallala Aquifer).

5.4 MANAGE TRADEOFFS: USE MULTIPLE POLICY INSTRUMENTS TO ACHIEVE MULTIPLE OBJECTIVES

By thinking in terms of these broader systems, there will be many objectives to achieve. Some objectives may be complimentary and have co-benefits, while others may be in conflict. Thus, tradeoffs will be inevitable and will need to be better understood and

properly managed. The process will ultimately be political in nature. Tradeoffs will be made across different users (including the environment), across present and future benefits, using different criteria (e.g. economic, political, social). Tradeoffs may also be across different spatial scales (e.g. downstream users and groundwater recharge). Analytical tools (e.g. multi-objective systems optimization) exist to help better understand and calculate these tradeoff frontiers (Haimes **et al.**, 1975; Loucks and van Beek, 2017). Under these conditions, as suggested by Tinbergen (1952), each policy objective should have its own instrument. For example, a single water productivity intervention cannot be used to both increase agriculture production and reduce basin wide consumption given that these objectives are largely in conflict.

Policymakers will face difficult choices in the selection amongst multiple interventions. Clear understanding of each instrument's objectives, operating scales, and stakeholders will be critical to assessing performance. Moreover, irrespective of intervention choice these will need to be embedded in a broader coherent policy framework that supports the water, energy, food and environmental security objectives of policymakers. This will require a high degree of coordination and collaboration across various sectors within government. Finally, the governance and institutional arrangements, including the processes in place to include stakeholder voice and input, will be critical to minimizing conflict.

5.5 MAXIMIZE AND SHARE BENEFITS IN AGRICULTURE: SET TARGETS FOR AGRICULTURAL WATER USE THAT MAXIMIZE THE BENEFITS FROM THE SECTOR AND ENSURE THAT FARMERS AND VULNERABLE POPULATIONS CAN THRIVE

Governments may envision different pathways for the agriculture sector and the role it plays in serving the economy and society. Depending on these goals (e.g. in terms of employment, economic growth, livelihood generation, poverty reduction, sustaining ecosystems), policymakers will need to determine how benefits, within defined water allocation boundaries, can be maximized for farming communities. That is, how can this available water for the agriculture sector achieve the most for society. At the same time, maximizing economic efficiency must be balanced against distributional aims, especially in the context of rural populations. Governments should ensure that benefits realized from agricultural water allocations are shared with vulnerable populations (e.g. women, children, disabled) such that these groups can thrive. For example, access to and control over water resources and its benefits in relation to agricultural production remains often unequal between female farmers and their male counter parts (Theis **et al.**, 2018). Hence, interventions to overcome economic and/or physical water scarcity requires likely different interventions and incentives. As such, increasing female farmers' incomes through agricultural water management interventions can improve family welfare as women tend to spend a higher proportion of their incomes on

associated expenses (i.e. food, school fees, and healthcare for their children) (Nicol **et al.**, 2015). This will build a more inclusive rural society and contribute to the SDGs on poverty, gender, and inequality.

5.6 EVALUATE, LEARN AND COMMUNICATE: PUT IN PLACE ITERATIVE PROCESSES OF LEARNING TO BUILD PROGRESS TOWARDS MAXIMIZING BENEFITS FROM AGRICULTURAL WATER USE WITHIN SUSTAINABLE LIMITS

All water productivity interventions (policy or technical) are social experiments in practice. Since changes in human behavior are intended, anticipated outcomes are never certain. Thus, frequent evaluation is needed throughout implementation. Learning during actual implementation is inevitable and should be incorporated and communicated broadly early-on to create greater chances for success. Only then can various water productivity approaches be improved upon to deliver optimal benefits from the agriculture sector, for farmers, vulnerable communities, and society, in a manner that preserves the opportunities for future generations in a sustainable environment.

6. Concluding remarks

Can water productivity improvements save us from global water scarcity? This depends on the difficult choices that policymakers will need to make about the water resource and who gets how much and when, and the resources that can be mobilized for related interventions. This is further complicated by the diverse goals and interests of different actors, and the multiple scales and systems within which agriculture water use is embedded. Agriculture water use will continue to be essential to achieving food security and supporting rural livelihoods and economies. The mark the sector has had on reducing poverty and hunger globally is clear. At the same time, population increase, unsustainable production and consumption patterns, and climate change are further constraining water resources and increasing stress for many. These realities call for urgent responses to achieve improved and more resilient agriculture water management, particularly in water scarce regions. This is essential to the urgently needed global transformation of the food system (Willett **et al.**, 2019).

While agriculture is responsible for about 70 percent of global water withdrawals, agriculture will be an important part of the solution to solving this global water scarcity challenge. Essential to this is first a better understanding of the multiple incentives of actors and water accounts at sub-basin, basin, and national levels. This requires significant investment in the capacity for countries to monitor and assess key hydrological and meteorological parameters. Only then can sustainable limits be determined and allocations across different water using sectors be made. Moreover, limits should be set in terms of maximum water consumption (instead of withdrawals) to prevent over-allocation and unintended negative impacts. It is unavoidable that significant allocations will go to agriculture water given the important role the sector plays in food security, employment, biomass-based production (including fodder, fuel and fiber) and in reducing poverty, hunger, and malnutrition. Policymakers will have a challenge in determining how best to generate benefits within these set water limits and ensure these benefits are broadly shared. Recognition and understanding of broad natural and human systems will be essential to minimizing unintended consequences. Moreover, given the multitude of objectives many of which may be in conflict, tradeoffs will need to be understood and managed and multiple instruments employed.

The stakes are high and accelerated action is needed, especially in the context of an uncertain climate change future and its implications on the dual challenge of food and water security. Sustainable water management across all sectors will be indispensable for climate-resilient growth and environmental integrity. At the same time, the goals of ending poverty and hunger will likely go well beyond the SDGs in 2030. Thus, more comprehensive thinking informed with better data and information, more integration between research and practice, and broader recognition of the landscape of actors and objectives will be critical to delivering benefits from the agriculture sector in a manner that preserves the opportunities for future generations. The principles given in this paper will help policymakers more effectively design water productivity interventions to achieve this.

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