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How to Assess Agricultural Water Productivity?

Looking for Water in the Agricultural Productivity and Efficiency Literature

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Abstract

Given population and income growth, it is widely expected that the agricultural sector will have to expand the use of water for irrigation to meet rising food demand; at the same time, the competition for water resources is growing in many regions. As a response, it is increasingly recommended that efforts should focus on improving water productivity in agriculture, and significant public and private investments are being made with this goal in mind. Yet most public communications are vague on the meaning of agricultural water productivity, and on what should be done to improve it. They also tend to emphasize water as if it were the only input that mattered.

This paper presents findings from a first attempt to survey the agricultural productivity and efficiency literature with regard to the explicit inclusion of water aspects in productivity and efficiency measurements, with the aim of contributing to the discussion on how to assess and possibly improve agricultural water productivity. The focus is on studies applying single-factor productivity measures, total factor productivity indices, frontier models, and deductive models that incorporate water. A key finding is that most studies either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle the basin level. It seems that no study on agricultural water productivity has yet presented an approach that accounts for multiple inputs and basin-level issues. However, deductive methods do provide the flexibility to overcome many of the limitations of the other methods.

This paper is a product of the Water Global Practice Group and the Agriculture Global Practice Group. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at sscheierling@worldbank.org.

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1. Introduction

It is widely believed that we are facing an unprecedented global water crisis. Without advances in water management and more integrated policy making in both developed and developing countries, water-related problems are expected to significantly worsen over the next several decades—with possibly dramatic consequences for the sustainability of economic growth, the integrity of important ecosystems, and the welfare of the poor who often end up bearing a disproportionate share of the costs. Among the key factors influencing this situation are water management issues in the agricultural sector. Two basic facts are critical for understanding agriculture's role in this water crisis. First, the agricultural sector is by far the largest user of water. Worldwide, irrigated agriculture accounts for about 70 percent of total freshwater withdrawals (Molden, 2007). An estimated 20 percent of cultivated land is irrigated, accounting for 40 percent of total agricultural production (Rosegrant *et al*., 2009). And, second, water use in agriculture also tends to have relatively low net returns as compared to other uses (Young, 2005). Thus, as water becomes scarcer in many parts of the world, other users tend to turn to agriculture as a potential source of water.

Besides a global water crisis, many experts also believe that we are facing an unprecedented global agricultural crisis. Continued population growth, rising meat and dairy consumption, and expanding biofuel use are increasing dramatically the pressure on agriculture worldwide. Observations of recent growth rates in the yields of major cereal crops have raised concerns that without major new investments in underperforming regions and strategies to continue increasing yields in high-performing areas agricultural productivity may not be rising fast enough to meet the likely demands (Ray *et al*., 2013). The availability of irrigation water will be a major factor in this regard, especially when other factors, such as the impacts from climate change, are also taken into account (World Bank, 2012). An indication of the increasing pressure is the unprecedented rise in transnational land acquisitions and the associated appropriation of water resources (Rulli *et al*., 2013).

Recent projections for food and agricultural production and related irrigation water needs assume that the world's population will reach about 9.6 billion people by 2050 (United Nations, 2013). Depending on the models employed and the assumptions and scenarios used, different forecasts have been made for food and agricultural production and the related irrigation water needs.[1] For example, projections by the Food and Agriculture Organization of the United Nations (FAO) for the period from 2005/2007 to 2050 indicate a growth rate of world consumption of agricultural products of 1.1 percent per

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[1] The Agricultural Model Intercomparison and Improvement Project (AgMIP) aims to unravel the main drivers of the differences observed in the outputs from ten global economic models assessing long-run agricultural production and demand (Nelson and Shively, 2014).

year. In order to meet this projected global demand, agricultural production in 2050 would have to be 60 percent higher than in 2005/2007, and irrigation water withdrawals would need to increase from 2,761 to 2,926 cubic kilometers (Alexandratos and Bruinsma, 2012). This projected increase of about 6 percent, which is based on rather optimistic assumptions, is quite worrisome given that other rapidly growing water demands, especially from the urban and environmental sectors, will also have to be met. If climate change impacts such as altered amounts and frequencies of precipitation events are factored in, the projections for irrigation water needs become even more alarming, especially in regions that already experience water-stress.

In order to at least partially respond to these two emerging crises involving agricultural water management, it is increasingly recommended that efforts should focus on improving water productivity in agriculture. Given the large amounts of water involved, and the widely held perception that water use in agriculture is relatively inefficient, it is thought that even small improvements in agricultural water productivity could have large implications for local and global water budgets. Such improvements would allow higher agricultural production with the same amount of water, or the same amount of agricultural production with less water. The water savings from the latter case could be reallocated to other higher-value uses.

In line with this thinking, many influential international institutions concerned with water management issues are promoting increases in agricultural water productivity as an important policy goal. For example, a key global water security target put forward by the Global Water Partnership (2000) is the increase in water productivity for food production by 30 percent in 2015. To avoid the intensification of the water crisis, the World Water Council (2000) envisions that about half of the increased demand for agricultural water use in 2025 should be met by increases in water productivity. The United Nations World Water Assessment Programme calls for crop water productivity increases with the aim of reducing pressure to develop new supply sources or increasing water allocation to agriculture (UNESCO, 2009). FAO (2012) considers demand management as an important option to cope with water scarcity, with increasing agricultural water productivity as the single most important avenue for managing water demand in agriculture. A number of recent reports of the World Bank Group have also called for a stronger focus on agricultural water productivity. For example, the water strategy *Sustaining Water for All in a Changing Climate* for the period FY10-13 mentions water productivity as a critical issue in agriculture (World Bank, 2010). The *Agriculture Action Plan* for the period FY13-15 points out that especially in regions where expanding the scope for irrigated agriculture is limited, more efforts are needed to improve the use of available water, by raising its productivity and sustainable use (World Bank, 2013).

Yet much of the reports and public communications calling for improvements in agricultural water productivity are not very helpful in illustrating what actually could or should be done to significantly increase agricultural production while attempting not to worsen water scarcity. A key problem is that the term "agricultural water productivity" is often used quite vaguely. If a definition is given or implied, it is usually along the lines of "more crop per drop", emphasizing water as if it were the only agricultural input that mattered.[2] Partly due to this lack of a clear conceptual framework, there is little systematic analysis on the instruments available for improving water productivity, including which interventions may be suitable and feasible in a particular situation. Furthermore, little attention is paid to monitoring and measuring the effects of different interventions, and empirical evidence of positive results (such as in terms of water savings) continues to be rare.

Nevertheless, in both developing and developed countries many public policies and large public and private investments are being made for improving agricultural water productivity. In developing countries, it is not uncommon for donor-supported investment projects, including those of the World Bank, to have increasing agricultural water productivity (and sometimes increasing agricultural water use efficiency) as a major development objective, with "crop per drop" measures as indicators for monitoring progress (Scheierling, 2013). In some cases the projects aim to induce a more productive or efficient use of the available irrigation water. In other cases, especially in water-scarce regions, the investments are increasingly expected to result in less water being used in irrigated agriculture and thus allow water transfers to other uses. A popular intervention is the provision of support to farmers for transitioning to more capital-intensive irrigation technologies. For the United States, several studies have shown that such interventions may reduce on-farm water applications, but do not necessarily provide *real* water savings, i.e. they do not reduce water consumption[3] and thus do not free up water resources for other uses (for example, Scheierling *et al*., 2006; and Ward and Pulido-Velazquez, 2008). Yet the Environmental Quality Incentives Program, first authorized in the 1996 farm bill, continues to help farmers buy more capital-intensive irrigation equipment, such as sprinklers and pipelines, to save water. Since 1997 subsidies of about $1 billion have been used to increase the "efficiency" of irrigation water use. Farmers who received subsidy payments have been shown to use some of their "water savings" (which occur mostly in terms of water applications) to expand the irrigated area or grow thirstier crops, and thus to

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[2] For example, an address of the United Nations Secretary General to a summit of the "Group of 77" developing countries stated: "…we need a Blue Revolution in agriculture that focuses on increasing productivity per unit of water, or ' more crop per drop'" (Annan, 2000).

[3] In crop production, the consumption of water is also called evaptranspiration (ET). This is the amount of water that is actually depleted or used up by the crops, i.e. —lost to the atmosphere through evaporation from plant and soil surfaces and through transpiration by the plants (and to a lesser extent embodied in plant products).

increase consumption (Nixon, 2013). In part this is because the respective institutional arrangements do not provide clarity on what should happen with perceived or real water savings (Lankford, 2013).

In this paper we argue that many of the complexities in the discussion about how to improve agricultural water productivity and efficiency are related to two key issues: first, the unique characteristics of water, such as its mobility and the interdependencies among its users; and, second, the multi-disciplinary nature of the topic, with each disciplines using different definitions and measures (and promoting different interventions)—and with relatively limited exchange between the disciplines so far.

Water has unique hydrologic and physical characteristics. As Young (2005) points out, unlike most other resources, water is mobile. Typically found in its liquid form, water tends to flow, evaporate, and seep as it moves through the hydrologic cycle. This makes it a high-exclusion cost resource, i.e. a resource for which exclusive property rights are relatively difficult and expensive to establish and enforce. Furthermore, water is also rarely completely consumed in the course of its "use" in agricultural production activities. Especially in crop production, it is not unusual to find that 50 percent or more of the water withdrawn from a water source is returned to the hydrologic system—in the form of surface runoff or subsurface drainage. Downstream users are affected by the return flows of upstream users. These externalities create pervasive interdependencies among users, and imply that the full costs of the related activity are not incorporated in individual users' decisions. Because of these characteristics, it is difficult to derive insights from what is observed on a field (or farm or irrigation system level) to the overall effects at the basin level.

Besides water's characteristics (yet partly related to them), the second key issue for the complexities surrounding the topic of agricultural water productivity and efficiency are the numerous processes and factors that play a role, with their relative importance varying from site to site. A wide range of disciplines is involved, including hydrology and hydrogeology, civil and irrigation engineering, agronomy and crop physiology, and economics. Each discipline tends to understand the terms productivity and efficiency in different ways and, even within one discipline, various productivity and/or efficiency terms are used or newly coined depending on the focus of study and the approach employed. For example, in civil engineering conveyance efficiency is an important term (defined as the ratio of the quantity of water received at the farm gate to the water withdrawn from a water source, such as a reservoir). Classical concepts in irrigation engineering are application efficiency (defined as the ratio of the amount of water stored by the irrigator in the root zone and ultimately consumed relative to the amount of water delivered to the farm), and irrigation efficiency (defined as ratio of the water consumed relative to the quantity of water applied or, alternatively, to the quantity of water withdrawn) (Jensen, 2007). Agronomists and crop physiologists, on the other hand, often use the term water use efficiency and apply different definitions (such as the ratio of plant biomass or yield produced relative to transpiration, or the ratio of yield relative to water consumed or water applied) (Hsiao *et al*., 2007).[4]

In the irrigation literature covering engineering and agronomy studies, such efficiency terms have dominated the discussion for many decades. A particularly important term has been irrigation efficiency, which can be increased significantly by a switch to more capital-intensive (on-farm) irrigation technologies. Productivity measures have become more widely used after Seckler (1996) pointed out that, in the field of water, "efficiency" was a tricky concept. Whereas in the energy sector in developed countries it was possible to cope with rising energy demand by increasing the efficiency of energy use, it may be erroneous to believe that through increases in irrigation efficiency (for example, by switching from gravity irrigation to drip irrigation) large amounts of water could really be saved and reallocated to other uses. Irrigation efficiency was inadequate to guide demand management at the basin level because it only addresses water delivery aspects for a farm or irrigation system, and implies that water not consumed by crops is wasted (or, vice versa, that water savings are achieved with an increase in irrigation efficiency) which is not necessarily the case in the context of basins where return flows are an important water source for downstream users. Thus local improvements in irrigation efficiency may not translate into basin-wide efficiency gains. In order to achieve real water savings, Seckler (1996) recommended focusing on increasing the productivity of water in irrigated agriculture. Subsequently, the term agricultural water productivity has been used increasingly in the irrigation literature. Many different definitions are being suggested and applied, mostly as single-factor productivity measures along the lines of "crop per drop" (and often similar to some of the definitions of water use efficiency in agronomy).

In the economics literature, including in the field of agricultural production economics (which has developed mostly separately from the irrigation literature), productivity and efficiency aspects are defined and analyzed in different ways. Productivity changes are understood to originate from various sources, including increased technical, scale and allocative efficiencies as well as technological progress. A range of methods has been applied for assessing productivity and efficiency, which can be grouped in different ways. One way that is useful for our purposes, following Ruttan (2002), is to distinguish between three

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[4] Hsiao *et al*. (2007) also show the relationship between engineering and agronomic efficiencies by developing an interesting framework using the concept of the chain of efficiency steps. When the production of an output is complicated and an input (such as water) goes through a chain of sequential steps ending in the output, the overall efficiency of the process can be quantified in terms of the efficiency of each of the component steps. The output in any step in the chain is the input in the following step. For example, if water is withdrawn from a reservoir for irrigated crop production, the efficiency of the first step would be conveyance efficiency, calculated as the ratio of water received at the farmgate to the water withdrawn; the second step would be farm efficiency, calculated as the ratio of water at the field edge to the water at the farmgate, and so on. In all, Hsiao *et al*. present a chain with three engineering and five agronomy-related efficiencies, with the last one being yield efficiency defined as the ratio of harvested yield to the plant biomass. At each efficiency step different interventions would have to be made to improve the respective efficiency measure, yet the effects would extend to the whole process.

main groups: single-factor productivity measures, total factor productivity (TFP) indices, and frontier models.

Single-factor (also called partial) productivity ratios or indices, relating output to only one input, are easy to calculate.[5] Yet they have a number of limitations, including that they are average, not marginal products; and because they are affected by the intensity of use of the excluded inputs, they give an incomplete picture of the underlying drivers of productivity change—especially when used in isolation. These issues were pointed out early on in the production economics literature.[6] Nevertheless, single-factor productivity ratios in the form of "crop per drop" continue to be widely used in the irrigation literature.

In contrast, the economics literature on agricultural productivity and efficiency mainly employs TFP indices and frontier models—not least because it is concerned with the inclusion not just of water, but also the other inputs (see Coelli *et al*., 2005, for an excellent introduction to this literature). TFP indices, the second group of methods, are particularly concerned with the incorporation of all inputs of the production process.[7] TFP indices compare a single output or an aggregate output index to an aggregate input index. Different ways of aggregation lead to different TFP indices, with Laspeyre, Paasche, Fisher, Törnqvist and Eltetö-Köves-Szulc indices being commonly used (Latruffe, 2010). These indices require both quantity and price information for the outputs and inputs included, and implicitly assume that all firms are efficient (which is unlikely to be true); hence, TFP changes over time are attributed to technological change.[8]

The third group of methods is frontier models, which measure efficiency as a potential input reduction or potential output expansion, relative to a reference "best practice" or efficient frontier, constructed from observed inputs and their output realizations. Techniques for defining the frontier can be classified into parametric and non-parametric methods. Parametric methods rely on specifying a production frontier and estimating its parameters econometrically. There are two types: deterministic frontier analysis that assumes that any deviation from the frontier is due to inefficiency, and stochastic

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[5] The early partial productivity studies in the agricultural sector focused on output per unit of land and labor, often in inter-country comparisons (see, for example, Hayami and Inagi, 1969).

[6] For example, Heady and Dillon (1961) in an inter-country comparison of production function estimates from farm samples emphasized that "the resultant average [computed as the mean output divided by the mean input of a resource] includes the product returns of all inputs, not simply the product return attributable to the single resource" (p. 590). Furthermore, a single-factor productivity measure does not account for the possibility of either factor substitution or output substitution (Latruffe, 2010).

[7] Because of the difficulty of capturing all of the inputs and outputs that interact in the production process, many studies refer to them as multifactor productivity (MFP), rather than TFP, indices.

[8] Besides using index numbers, TFP changes can also be calculated from econometric estimates of a production function or frontier.

frontier analysis (SFA) that also allow for statistical noise.[9] Non-parametric methods, on the other hand, use mathematical programming techniques to construct piece-wise a surface (or frontier) over the output-input space and then calculate the level of inefficiency as the distance to the frontier. The most popular method to do this is data envelopment analysis (DEA) (Latruffe, 2010).[10]

In addition to these three groups of methods, there is a fourth group that is not much discussed in the agricultural productivity and efficiency literature but constitutes an important part of the agricultural and irrigation water economics literature. Following Young (2005), this group can be termed deductive, and includes various alternatives such as the residual imputation method, mathematical programming, hydroeconomic models, and computable general equilibrium (CGE) models. In contrast to the parametric methods, which employ inductive logic (in this case econometric procedures) to infer generalizations from individual observations, deductive methods apply constructed models comprising a set of behavioral postulates (such as profit maximization) and assumptions to reason from general premises to particular conclusions. They are based on the specification of a physical production function and assume that firms operate on the frontier. Because of their ability of modeling different scenarios, deductive methods are useful for policy analysis and project planning.

The literature related to agricultural water productivity and efficiency is extensive, yet fragmented among disciplines. This paper reports on the findings of a survey of the agricultural productivity and efficiency literature with regard to the explicit inclusion of water aspects in productivity and efficiency measurements, with the aim of contributing to the discussion on how to assess and possibly improve water productivity in the agricultural sector. The focus is on studies that apply one of the four groups of methods and make an effort to incorporate water quantity aspects, i.e., single-factor productivity measures, TFP indices, frontier models, and deductive methods. Water quality aspects and other agricultural activities besides irrigated crop production are not included. To our knowledge, this is the first attempt to undertake a review and analysis of this type. Given the extensive literature on agricultural productivity and efficiency, the survey does not attempt to be exhaustive. A key finding is that most studies presented in the agricultural productivity and efficiency literature either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle the basin-level. It seems that no study on agricultural water productivity has yet presented an approach accounting for both multiple inputs and basin-level issues. However, deductive

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[9] This is modeled through a composed error structure, with a one-sided component measuring inefficiency and a two-sided symmetric term capturing statistical noise.

[10] DEA and SFA can also be used to obtain the distance measures required for the Malmquist TFP index, which provides a decomposition into technological and efficiency change.

methods—while not inherently equipped with a multi-factor, basin-level framework—do provide the flexibility to overcome many of the limitations of the other methods.

The remainder of the paper is organized as follows. Conceptual issues are further elaborated in section 2, providing a background to the literature review in sections 3 to 5. Studies, mostly from the irrigation literature, that employ single-factor productivity measures with a focus on water are reviewed in Section 3. Section 4 examines studies with multi-factor approaches, comprising TFP indices and frontier models, from the agricultural economics literature on productivity and efficiency. Deductive methods from the irrigation water economics literature are presented in section 5. Finally, section 6 provides a discussion and conclusions.

2. Conceptual Issues

In discussing conceptual issues, we start out by providing a brief exposition of the definitions of efficiency and productivity in economics (Figure 1). Then a series of illustrations is presented which focus on two key dimensions. The first dimension is the number of inputs considered: a distinction is made between single-factor (water only) and multi-factor approaches; and the second dimension is the scale at which water productivity issues are tackled: limited to the field/farm/ irrigation system level, or also incorporating basin level aspects (i.e., explicitly taking into account return flows). The first two illustrations analyze the limitations of single-factor productivity measures, such as “crop per drop”, especially with the incorporation of return flows—which are key to understanding the physical externalities generated within the agricultural sector (Figure 2) and also between the agricultural and other sectors (Figure 3). The following illustrations (Figures 4 to 6) seek to capture the elements that should ideally be included in studies tackling agricultural water productivity: a multi-factor approach, a distinction between efficiency gains and technological progress, and the basin-wide view (i.e., accounting for return flows). Finally, a link is drawn between different notions of efficiency from the irrigation engineering and economics literatures (Figure 7).

Productivity is generally defined as the ratio of the output(s) to the input(s) that a firm uses. It is widely used as a performance measure where larger values of the ratio are associated with better performance. It can be simply measured as a single-factor productivity indicator, relating one output to one input. The more comprehensive measure of total factor productivity (TFP) is a ratio that relates the aggregate of all outputs to the aggregate of all inputs. Potential productivity improvement can be assessed when firms are compared to a benchmark: with cross-sectional data, firms are compared with each other in the same period, while time-series data allow comparisons over time. In the former case, a firm can increase its productivity relative to other firms by improving its technical efficiency, allocative efficiency, and/or scale efficiency. In the latter case, technological change is an additional source of productivity growth; it involves an upward shift of the production function, implying that a firm can produce more output for each level of input (Latruffe, 2010).

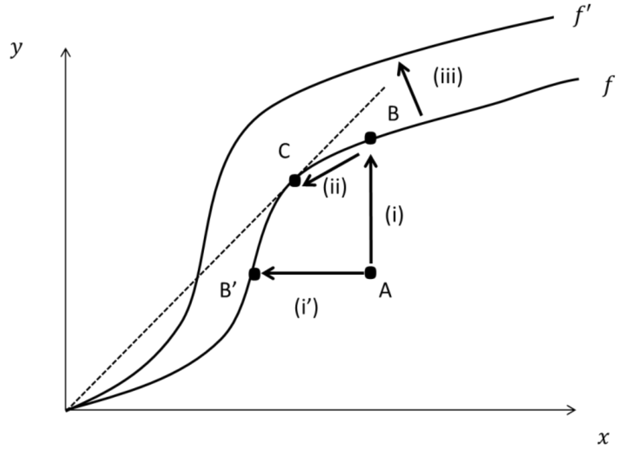

Figure 1. Sources of Improvements in Productivity
Source: Based on Coelli *et al.*, 2005.

To illustrate the different sources of productivity increases, Figure 1 shows a single input-single output case ($y = f(x)$), where f is the production frontier. A ray through the origin has the slope y/x, and thus provides a measure of average productivity. Initially the firm is operating at point A. Productivity may improve through (i) increased technical efficiency, i.e. the same level of output is produced with less input (move from point A toward point B') or more output is produced with the same level of input (move from point A toward point B) which, in both cases, involves a move toward the production frontier; (ii) economies of scale, i.e. operating at the point of (technically) optimal scale where the ray from the origin is a tangent to the production frontier (move from point B to point C); and (iii) technological change, which may be represented by an upward shift in the production function (move from f to f').

If prices are included in the analysis (in addition to the physical quantities and technical relationships outlined above), another source of productivity change, allocative efficiency, can be considered. In input selection, for example, allocative efficiency involves selecting that mix of inputs that produces a given level of output at minimum cost.

Figure 2 illustrates a central potential pitfall of relying on single-factor productivity measures, such as "crop per drop" ratios, to measure agriculture water productivity. The necessity of tackling productivity issues beyond the field (or farm or irrigation system) level is demonstrated using a simple example. An irrigated area is initially assumed to produce 100 kg of a particular crop. Water is withdrawn from a river and delivered to the area in a canal. About 10 percent of the water withdrawn is lost in the canal to seepage. Seepage and water not consumed by the crop are assumed to return via a shallow aquifer to the river.

In case (i), on-farm irrigation efficiency (defined as the ratio between water consumed and water applied) is 40 percent. Water consumption amounts to 36 m^3, composed of 24 m^3 of beneficial consumption (which is necessary for plant growth) and 12 m^3 of non-beneficial consumption (which may comprise, for example, evaporation from soil surfaces). Thus 90 m^3 of water would have to be applied to the irrigated area, and 100 m^3 withdrawn from the river.

Case (ii) shows the effects from an improvement in on-farm irrigation efficiency to 60 percent (because the farmer moved to a more capital-intensive irrigation technology, for example, from a gravity system to sprinklers). Water application could then be reduced from 90 m^3 to 60 m^3, and withdrawals from 100 m^3 to 67 m^3. The respective crop per drop values increase significantly.[11] Yet because water consumption does not change[12], the value for agricultural water productivity in terms of water consumed would stay the same, as would the river flow downstream of the irrigated area.

Case (iii) presents the situation where the farmer, after switching to a higher on-farm irrigation efficiency, would continue to withdraw the original amount of water and spread it over an expanded area. Yield would increase to 150 kg, and water consumption to 54 m^3. The values for agricultural water productivity would be the same as in case (ii), yet the river flow downstream is reduced from 164 m^3 to 146 m^3.

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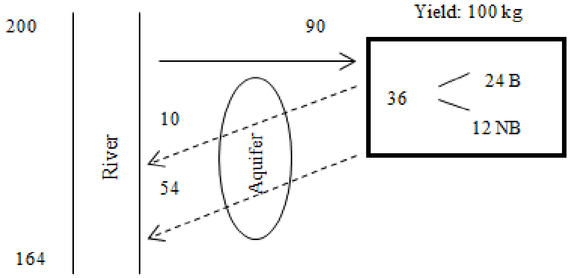
[11] In terms of the framework presented in Figure 1, this increase is the result of the improved technology used by the farmer (i.e., a shift in the production frontier), not the efficiency with which a given technology is used (i.e., the distance to the production frontier).

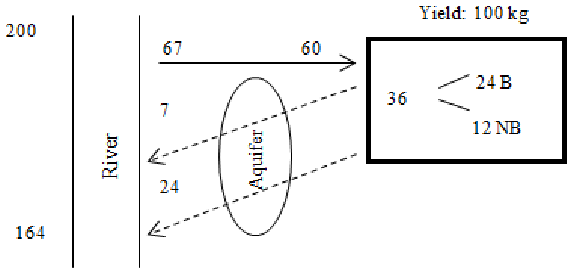
[12] With constant crop yield, a constant level of water consumption is assumed regardless of the level of water application. This assumption is also made in the following cases.

Case (i): 40% Irrigation Efficiency



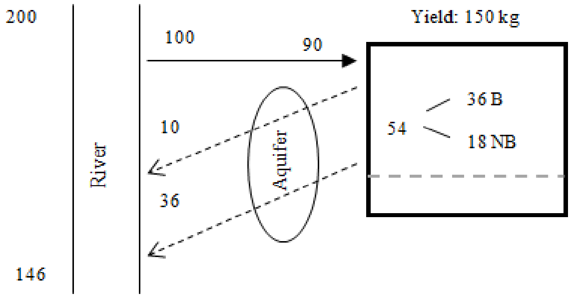
	Water Measure (m³)	AWP (kg/m³)
Water withdrawn	100	1
Water applied	90	1.1
Water consumed	36	2.8

Case (ii): 60% Irrigation Efficiency, No Water Spreading



	Water Measure (m³)	AWP (kg/m³)
Water withdrawn	67	1.5
Water applied	60	1.7
Water consumed	36	2.8

Case (iii): 60% Irrigation Efficiency, Water Spreading



	Water Measure (m³)	AWP (kg/m³)
Water withdrawn	100	1.5
Water applied	90	1.7
Water consumed	54	2.8

Note: AWP = agricultural water productivity; B = beneficial consumption; NB = non-beneficial consumption

Figure 2. Effects of Improved On-Farm Irrigation Efficiency and Water Spreading on Agricultural Water Productivity (Defined in Terms of Yield Divided by Water Withdrawn, Water Applied, and Water Consumed) and on River Flow

Source: Authors.

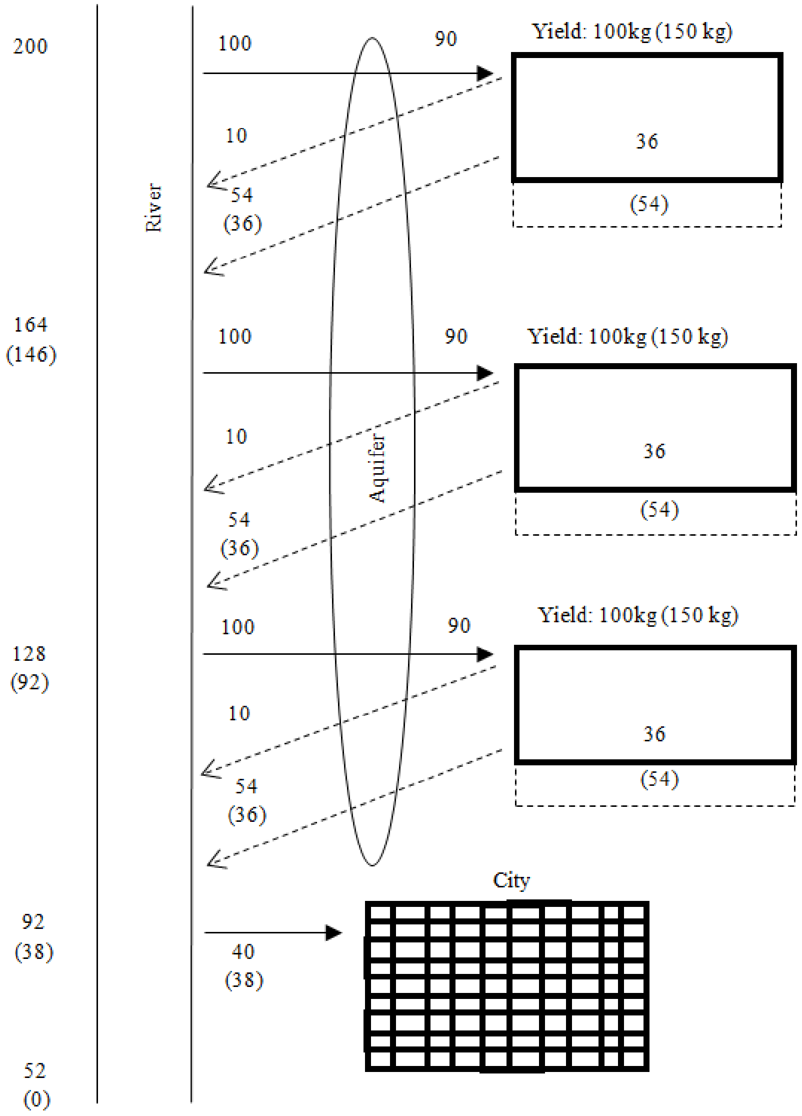


Figure 3. Basin-wide Effects of an Increase in On-Farm Irrigation Efficiency from 40% to 60% with Water Spreading (in Brackets)

Source: Authors.

Figure 3 shows the case of a basin with several water users. Building from the cases (i) and (iii) of Figure 2, it is assumed that two additional irrigated areas with similar features and a city requiring 40 $m^3$of water consumption are located downstream. Initially (i.e. case (i)) the three irrigated areas operate with an on-farm irrigation efficiency of 40 percent, and each produces a yield of 100 kg. Under these circumstances the city can be supplied with the necessary water of 40 m^3, and the river flow downstream amounts to 52 m^3which would be considered sufficient for environmental purposes.

If the irrigated areas switch (now, case (iii)) to an on-farm irrigation efficiency of 60 percent and continue to withdraw the same water amounts as before (for example, because of the ownership of water rights that are formulated in terms of withdrawals), they can spread the water on more land and increase their combined yield from 300 kg to 450 kg (see the numbers in brackets). However, the return flows from the irrigated areas would decrease and the city would now have water problems. Even if the city withdrew all the water left in the river, it would only receive 38 m^3. In such a situation negotiations between upstream and downstream users may help to resolve the problem. The city could, for example, subsidize the farmers in the irrigated areas to adopt additional measures to reduce non-beneficial consumption by two- thirds. This would guarantee the city's water needs, but the environmental uses further downstream might still be negatively affected.

While Figures 2 and 3 make a compelling case for revisiting the use of crop per drop ratios as productivity measures and for addressing productivity issues at the basin-wide level, they are also based on a conceptual framework that suffers from three critical shortcomings: only one input (water) is considered; productivity increases only stem from technological progress (possible efficiency gains are not considered); and prices are not accounted for. Figures 4 to 7 strive to address these shortcomings.

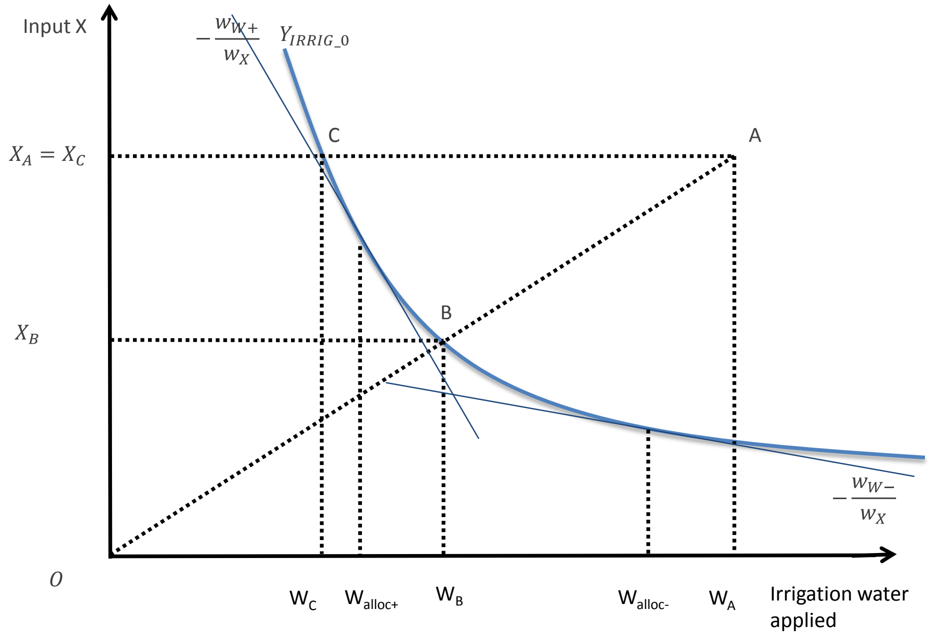


Figure 4. Effects of Input-Oriented Technical Efficiency, Water-Specific Technical Efficiency, and Allocative Efficiency on Water Applied and Other Input Use

Source: Authors.

Figure 4 illustrates a multi-factor framework in which the concepts of technical efficiency and allocative efficiency are discussed. It represents the situation where a farmer, originally at point A, produces a given crop in the quantity Y_{IRRIG_0} by applying irrigation water in the amount of W_A (with a traditional technology, say a gravity system) and all other inputs in the amount of X_A.[13] Following Karagiannis *et al.* (2003), the water-specific technical efficiency is measured by the ratio of two distances, $[X_A C]/[X_A A] = W_C/W_A$. This measure determines the minimum amount of water applied (W_C), and also the maximum potential reduction in water applied ($W_A - W_C$) that would still allow the production of Y_{IRRIG_0} while keeping all other inputs at X_A.

Input-oriented technical efficiency would imply a move to point B where the quantity of water applied would decrease to W_B. This potential reduction ($W_A - W_B$) is smaller than ($W_A - W_C$), with the latter considered as an upper bound.

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[13] Input X in Figure 4 (and in the following figures) is a composite of all the other inputs except water that can be modified by the farmer in the short-run, typically during a cropping season. The level of capital used, including the type of irrigation technology, is assumed to be constant during this timeframe.

Taking into account the prices of inputs, the farmer could strive to be efficient from an allocative point of view, reaching a level of water applied of W_{alloc-} or W_{alloc+} (with $W_{alloc-} > W_{alloc+}$) depending on the price of water, W_{W-} or W_{W+} (with $W_{W-} < W_{W+}$), respectively.

Figure 5 illustrates that basin-wide issues can also be taken into account in the multi-factor framework. It goes beyond the situation presented in Figure 4 by adding the consideration of return flows.

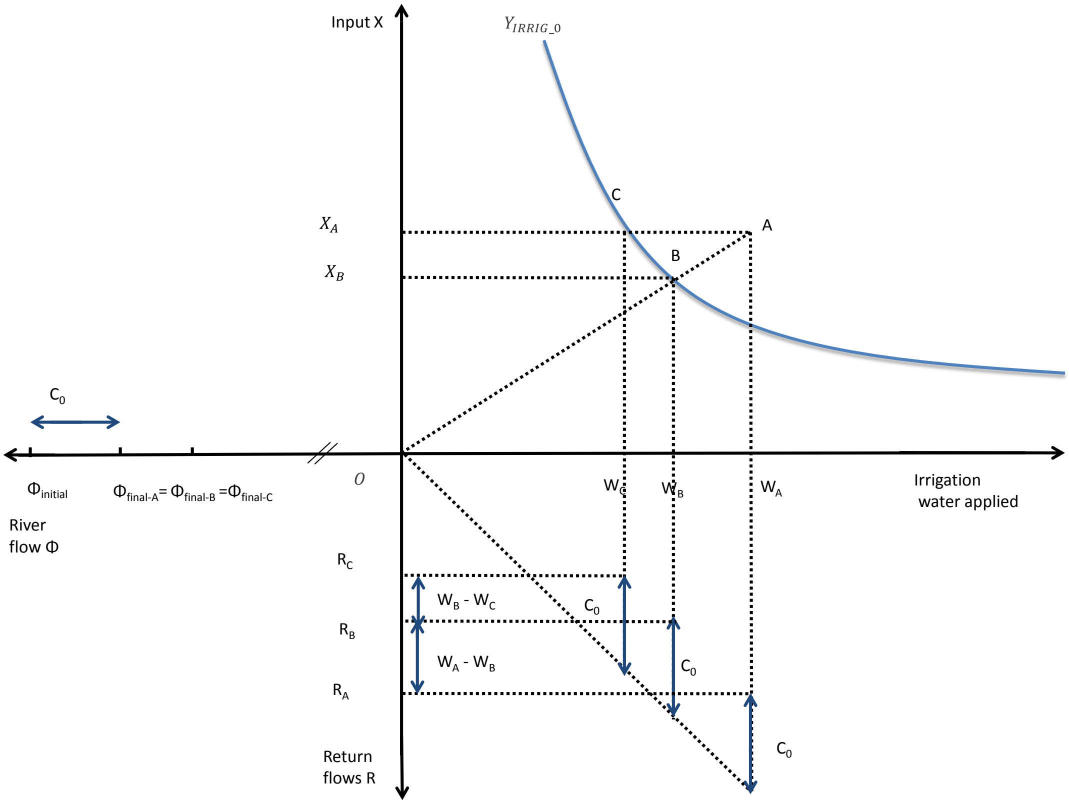

Figure 5. Effects of Input-Oriented Technical Efficiency and Water-Specific Technical Efficiency on Water Applied and Other Input Use, and the Associated Water Consumed, Return Flows, and River Flow Downstream

Source: Authors.

Initially a farmer is at point A where the quantity of water applied is W_A, other inputs are used in quantity X_A, and the return flow is equal to R_A, with $R_A = W_A - C_0$, C_0 being the quantity of water consumed to produce quantity Y_{IRRIG_0} of output. This results in a river flow downstream amounting to $\Phi_{final\_A} = \Phi_{initial} - (W_A - R_A) = \Phi_{initial} - C_0$.

With better management, the farmer can reach input-oriented technical efficiency at point B, applying W_B of water and X_B of other inputs. The return flow is now R_B, with $R_B = W_B - C_0 = R_A -$

$(W_A - W_B)$. The difference in return flows between point A and point B on the frontier is equal to the difference in water applied since in both cases the quantity of water consumed is equal to C_0, used to produce the quantity of output Y_{IRRIG_0}. As a consequence, river flows downstream are the same in both situations, $\Phi_{final\_A} = \Phi_{final\_B} = \Phi_{initial} - (W_A - R_A) = \Phi_{initial} - C_0$.

Water-specific technical efficiency at point C leads to similar results as in the other two situations, with the quantity of water consumed being the same at C_0, and thus also the river flow downstream being the same.

The potential effects of technological progress in irrigation are shown in Figure 6, both at the farm and basin level. Figure 6 aims to reproduce the situation depicted in Figure 2, and go beyond it in two respects: by using an input-oriented setting (with isoquants), and introducing a multi-factor framework.

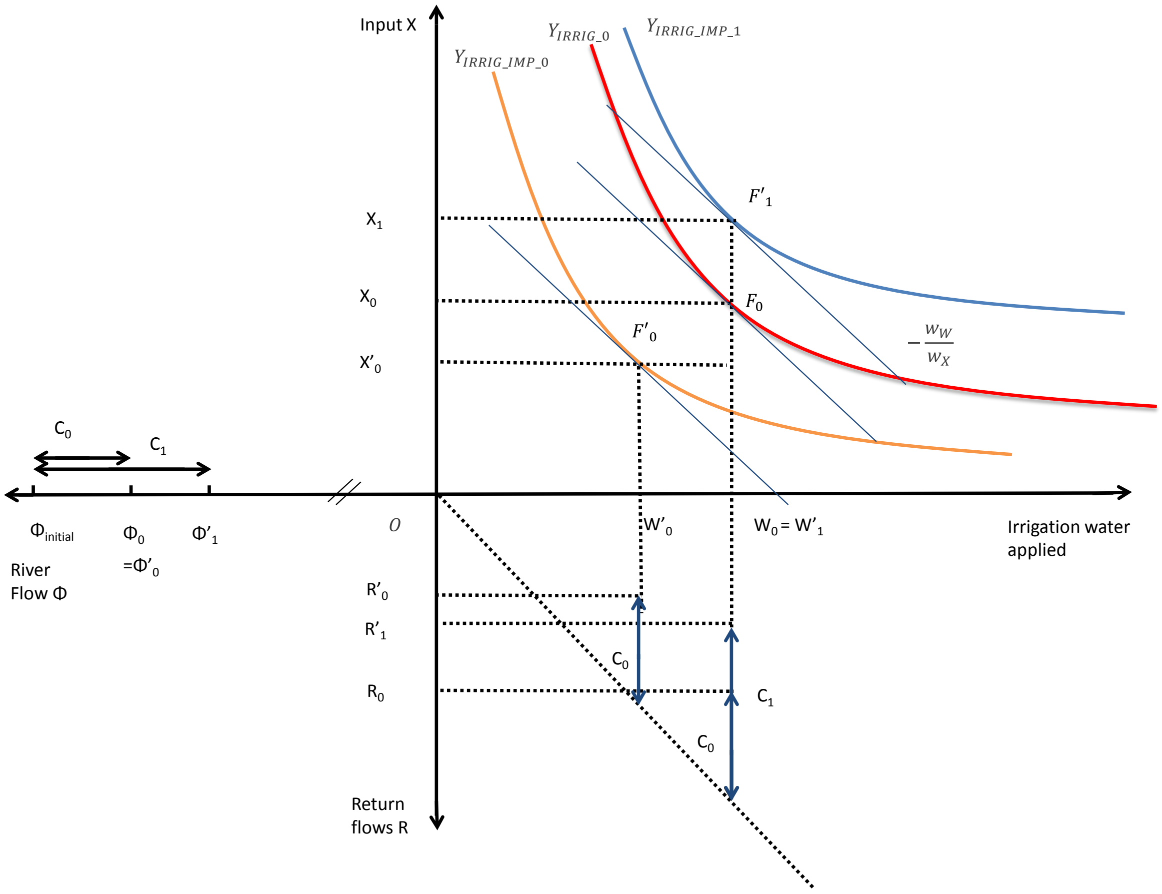

Figure 6. Effects of Technological Progress on Water Applied and Other Input Use, and the Associated Water Consumed, Return Flows, and River Flow Downstream

Source: Authors.

If a farmer switches to a more capital-intensive irrigation technology (say, from a gravity system to a sprinkler system), the level of inputs used (notably the quantity of water applied) to produce the quantity Y_{IRRIG_0} of output is usually reduced, i.e. the isoquant moves downwards and is now labelled $Y_{IRRIG\_IMP\_0}$ (with $Y_{IRRIG\_IMP\_0} = Y_{IRRIG\_0}$). Alternatively, the new irrigation technology can be used to apply, for example, the same amount of irrigation water and increase production to level $Y_{IRRIG\_IMP\_1}$ (as in Figure 2, we assume a 50 percent production increase, i.e. $Y_{IRRIG\_IMP\_1} = 1.5\ Y_{IRRIG\_0}$).

These situations are illustrated in Figure 6. Production combinations are only considered if they are technically efficient, i.e. those located on one of the three isoquants, and also efficient from an allocative perspective, i.e. the three isoquants satisfy the tangency condition with the relative prices of inputs at points $F_0, F'_0, and\ F'_1$ (the slopes of their respective isoquants are equal to $-W_W/W_X$).

Considering the situation with a gravity system, at point F_0 the quantity of water applied is W_0, leading to return flows at level $R_0 = W_0 - C_0$, and a river flow downstream amounting to $\Phi_0 = \Phi_{initial} - (W_0 - R_0) = \Phi_{initial} - C_0$. [This situation is the analogous of case (i) in Figure 2.]

Switching to the sprinkler system at point F'_0, fewer inputs are used, in particular less water is applied, now amounting to W'_0. However, the river flow downstream does not change compared to the previous situation, as the quantity of water consumed at level C_0 is also not changed—the same output quantity is still produced: $\Phi'_0 = \Phi_{initial} - (W'_0 - R'_0) = \Phi_{initial} - C_0 = \Phi_0$. [This situation is analogous to case (ii) in Figure 2.]

A third situation is considered in which the switch to the sprinkler system leads to an increase in production, now at level $Y_{IRRIG\_IMP\_1}$, with the farmer operating at point F'_1. With the same quantity of water applied as in the first case, i.e. $W_0 = W'_1$, the farmer now uses a higher level of other inputs, i.e. X_1. Return flows decrease with respect to the initial situation (since the quantity of water consumed with a higher yield C_1 is now $C_1 > C_0$), and the river flow downstream is $\Phi'_1 = \Phi_{initial} - (W_0 - R'_1) = \Phi_{initial} - C_1 < \Phi_0$. [This situation is analogous to case (iii) in Figure 2.]

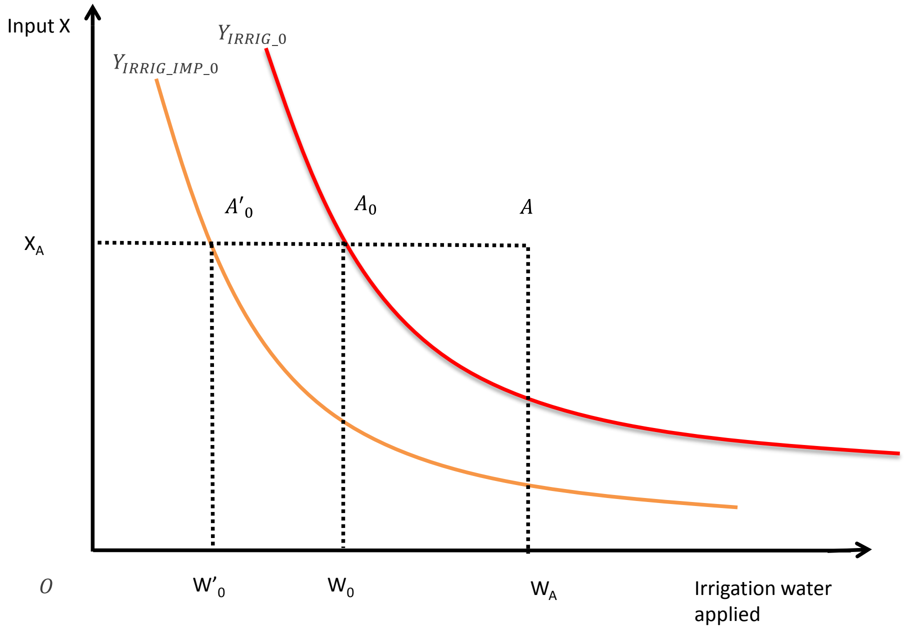

Figure 7. Relationship of On-Farm Irrigation Efficiency with Water-Specific Technical Efficiency and Water-Specific Technological Progress

Source: Authors.

Figure 7 shows a link between the different notions of efficiency. On-farm irrigation efficiency, widely used in the irrigation engineering literature, is usually defined as a ratio of water consumed divided by water applied. It can be argued that on-farm irrigation efficiency straddles two economic notions: technological progress (the distance between two isoquants) and input-oriented technical efficiency (the distance from a point in the input space to the isoquant). In both cases, the movement between two isoquants or towards an isoquant is achieved while keeping all other inputs (X) at the same level; hence the economic notions considered here are restricted to being "water-specific". Let W_C and W_A be the quantities of water consumed and applied to reach an output level Y_{IRRIG_0}. On-farm irrigation efficiency IE can then be defined by the ratio $IE = \frac{W_C}{W_A}$.

The farmer initially operates at point A. This could be the result of either water-specific technical inefficiency and/or the absence of an capital-intensive irrigation technology. If the factors causing water-specific technical inefficiency would be addressed, the farmer could move to point A_0 and then apply water in the quantity of W_0; if the factors preventing water-specific technological progress would also be addressed, the farmer could move to point A'_0 and only apply W'_0.

Defining $TE_{WS} = W_0/W_A$ as water-specific technical efficiency, and $TP_{WS} = W'_0/W_0$ as water-specific technological progress, the relationship of on-farm irrigation efficiency with these notions can be expressed as follows:

$\mathrm{IE} = \frac{W_C}{W_A} = \frac{W_0}{W_A} \cdot \frac{W'_0}{W_0} \cdot \frac{W_C}{W'_0} = \mathrm{TE}_{WS} \text{ x } \mathrm{TP}_{WS} \text{ x } \mathrm{IE}_{\max}$, with $\mathrm{IE}_{\max}$ being the highest level of technical irrigation efficiency attainable, i.e. involving the most skilled farmer and the most capital-intensive irrigation technology.

Overall, the illustrations presented in Figures 1 to 7 provide insight into some of the key issues that the agricultural water productivity and efficiency literature seeks to address. Employing the two dimensional framework introduced above with, first, the scale considered (at the field/farm/irrigation system level or also at the basin level, taking into account return flows) and, second, the number of inputs considered (single-factor, or water only, and multi-factor approaches), it appears that most methods presented in the agricultural water productivity and efficiency literature demonstrate strength in one dimension only—i.e., they are either a multi-factor approach but do not tackle the basin-level, or they are able to incorporate field- and basin-levels but focus only on a single inputs (water). To our knowledge, no study on agricultural water productivity has yet presented an approach accounting for both multiple inputs and basin-level issues. However, deductive methods—often applied in irrigation water economics—do provide the flexibility to overcome those limitations. The literature review below starts out with a look at the irrigation literature on agricultural water productivity and efficiency, followed by the economics literature.

3. Single-Factor Productivity Measures

The use of single-factor productivity measures is dominant in productivity-related studies in the irrigation literature, and its origin can be traced to Seckler (1996). Referring to earlier findings (such as Keller and Keller, 1995), Seckler pointed out that the classical concept of "irrigation efficiency"—widely used in irrigation engineering and, in its basic form, defined as the ratio of water consumed by crops to the water withdrawn or applied—was inadequate to guide water demand management at the basin level. This is because water that is not consumed by crops is not necessarily wasted in the context of basins where return flows are an important water source for downstream users. Thus local improvements in irrigation efficiency may not translate into real water savings at the basin level. Because of this, he recommended focusing less on improving irrigation efficiency and more on increasing the productivity of water in irrigated agriculture. Without further defining "agricultural water productivity", Seckler (1996) advocated measures for improving it, such as increasing output per unit of water consumed, reducing water losses to sinks, reducing the pollution of water, and reallocating water from lower valued to higher valued uses.

Following Seckler (1996), other authors—mainly affiliated with the International Water Management Institute (IWMI)—suggested definitions for agricultural water productivity (Molden, 1997;

Molden and Sakthivadivel, 1999; and Molden and Oweis, 2003). These definitions were subsequently refined and applied in numerous articles in the irrigation literature.[14] Water productivity in agriculture was understood as agricultural output per unit volume of water. The numerator of the ratio could be in physical terms, such as kilograms of agricultural production or marketable crop yield; or, in so-called "economic" terms, a dollar value, such as gross or net value of product. The denominator could be expressed as water supplied or depleted (such as consumed by evapotranspiration, and/or lost in a sink where it cannot be readily reused). Thus, when choosing a particular numerator and denominator, a decision had to be made about 'which crop' and 'which drop' to include, taking into account factors such as the relevant scale (i.e. field, farm, irrigation system, or basin), the stakeholders, and data availability. For example, it was proposed that at the farm level the ratio of kilograms of yield relative to evapotranspiration would be suitable, whereas at the basin level the ratio of a dollar value relative to the available water would be appropriate (Molden *et al*., 2003).

A review of the single-factor studies shows that various methods have been used to measure agricultural water productivity across crops, basins, countries, regions and time periods, with the aim of identifying critical factors to articulate recommendations for policy reform and interventions to "close the gap" in the water productivity findings and, thus, help alleviate rising water scarcity. Substantial differences in spatial and temporal water productivities have been documented—depending on the particular definition of "water productivity" chosen, but also with the use of the same definition. For example, water productivity for wheat in terms of kilograms of yield relative to cubic meters of evapotranspiration among farms in an irrigation district in Iran varied from 0.76 to 0.98, while in terms of kilograms of yield relative to cubic meters of transpiration it ranged from 1.11 to 1.26 (Vazifedoust *et al*., 2008).[15] Most studies use such findings to argue that a large scope exists to increase yields and/or save water and, thus, to improve water productivity. Many explanations for the differences are presented, usually without further analysis with regard to the significance and/or magnitude of the different factors that may cause the variations. The identified policy implications tend to be wide-reaching, but often not supported with robust evidence from the analyses carried out.

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[14] A search in the databases Water Resources Abstracts, Agricola, and EconLit was carried out using the terms "water productivity," "crop per drop," and "water use and productivity" in the title of studies. This resulted in 257 articles from peer-reviewed journals; seven studies were identified in EconLit.

[15] Some studies thus recommended that further analyses should be carried out to increase the sample size (for example, regarding the number of irrigation schemes, as in Sakthivadivel *et al*., 1999). Also, for better comparisons of estimates, it was recommended that water productivity indicators should be used in a more standardized way (for example, with regard to fresh matter or dry matter for grain yield in the numerator; or the period taken into account in the denominator, such as the entire growing season or only the time from sowing to harvest), and/or that information on these aspects should at least be included in the studies (Bessembinder *et al*., 2005).

A few authors in the irrigation literature have critiqued some of the studies' approaches and assumptions. In an early critique, Barker *et al*. (2003), for example, pointed out that while a higher water productivity tends to be viewed as inherently better than a lower one, this may not be the case from the perspective of the farmer or the economy as a whole. The example they use is that a management practice that increases water productivity may require more labor and other inputs, and therefore might not be cost-effective. (A further example of their point, based purely on physical relationships, is provided in Figure 2. It shows that changes in water productivity ratios mask important underlying processes and effects, and are therefore of limited use as indicators for characterizing changes resulting from interventions with regard to yield increases, water applied, or water saving.) Below is a more detailed discussion of selected studies on single-factor productivity measures from the irrigation literature.

Traditionally, agricultural water productivity has been derived by measurements of crop yields and water use at experimental stations and farmer fields. Such studies typically try to control for other relevant inputs. They tend to be time- and resource-intensive, and their results cannot be easily extrapolated to other conditions. An example for this type of study is by Arbat *et al*. (2010) who examine the effect of subsurface drip irrigation emitter spacing on water productivity (defined as corn grain yield with 15.5 percent wet-basis moisture content divided by total crop water consumed) in Kansas, and find no significant impact.

Based on a literature review that yielded of 84 publications with data from field experiments, Zwart and Bastiaanssen (2004) compared measured water productivity values (in terms of marketable crop yield over actual evapotranspiration) of major crops. They find wide ranges, amounting to 0.6-1.7 kg m^{-3} for wheat, 0.6-1.6 kg m^{-3} for rice, and 1.1-2.7 kg m^{-3} for maize, and interpret these to indicate "tremendous opportunities for maintaining or increasing agricultural production with 20-40 percent less water resources" (p. 115). Without more in-depth analysis, they discuss three factors that influence the soil-plant-water relationship as key for explaining the large variations, including climate, irrigation water management, and soil management.

More recently, a range of studies used agrohydrological models in combination with measured data to estimate crop water productivities. An example is Vazifedoust *et al*. (2008) who applied the soil water atmosphere plant (SWAP) model calibrated with farmers' field data to an irrigation district in Iran. Water productivity indicators were estimated in different physical and "economic" terms for four key crops. The authors conclude that the substantial differences between the indicators expressing yield over evapotranspiration and yield over irrigation water applied indicated "the need for replacing the traditional irrigation system with a more efficient one" (p. 101).

Other studies combined agrohydrological modeling with remote sensing and geographical information systems (GIS) data to assess water productivity at larger scales. For example, van Dam *et al.* (2006) used the SWAP model, together with geographical and satellite data, to calculate water productivity using different definitions in a district in India. The authors found that the ratio of yield per m^3 of evapotranspiration for key crops, such as wheat and rice, could be derived relatively cheaply by remote sensing; but more resource-intensive modeling allowed them to estimate additional definitions of water productivity, and also assess the effects of alternative management scenarios (such as better nutrient supply and pest control) on the ratio of yield over evapotranspiration for the key crops. Better crop management, for example, was found to increase the ratio.

Some studies also modeled crop water productivities on a global scale. Pointing out that most previous crop growth models were used for site-specific applications, Liu *et al*. (2007) integrated GIS into the environmental policy integrated climate (EPIC) crop growth model in order to extend the model for wheat on a global scale, addressing spatial variability of yield and evapotranspiration as affected by climate, soil, and management factors. Simulated yields were compared to FAO statistical yields and found to be in good agreement. Estimated crop water productivities differed significantly within and across countries. Western European countries had relatively high values (>1.2 kg m^{-3}), whereas low values (<0.4 kg m^{-3}) prevailed in most African countries. According to the authors, the differences "suggest that global water use could be reduced through food trade" (p. 478).

Zwart *et al*. (2010a, 2010b) developed a model called WATPRO that is based on remote sensing-derived input data sets, and estimated directly yield over evapotranspiration. The model was also applied to wheat on a global scale. Large variations in water productivities were found, with an average estimate for the ten major wheat producing countries of 0.93 kg m^{-3}. The authors argued that results from their model "facilitate the planning of food production in relation to limited water resources for agriculture" (p. 1625).

A few studies with single-factor productivity estimates analyze in a more rigorous manner the effect of other factors on their findings for water productivity. One approach, chosen by Belloumi and Mattoussi (2006), was to estimate crop yield functions with irrigation water as one of the explanatory variables (thus assessing the partial effect of the water input on crop yield variations while controlling for the effect of other input variables). They applied a Cobb-Douglas function to cross-section data on date yields in different oasis farms in Tunisia, and a linear function to related values for water productivity (in terms of irrigation water applied). They found water salinity to be a key factor that contributes to both yield and water productivity differences. Another approach based on panel data analysis was used by Alauddin and Sharma (2013) to explore inter-district differences in rice water productivity (in terms of consumptive use) in Bangladesh. They first applied factor analysis to derive representative dimensions, and identified agricultural intensification and technological diffusion as key explanatory variables. Employing Granger causality tests, they further explored the role of these two factors on water productivity changes, suggesting that technological diffusion was a causal factor of water productivity in the majority of districts in Bangladesh. Then they employed generalized least squares estimates and found that technological diffusion had a positive effect on inter-district water productivity differences while agricultural intensification and policy transition towards deregulated markets decreased water productivity.

4. Multi-Factor Approaches: TFP Indices and Frontier Models

Whereas single-factor productivity measures are mostly found in the irrigation literature, multi-factor measures—in particular TFP indices and frontier models—dominate the productivity and efficiency-related literature in agricultural production economics.

TFP indices have been employed in a large number of empirical studies, mostly at the national level but more recently also at subnational levels. The usual TFP indices account for marketed outputs of goods and services but tend to disregard items , such as water, that are usually not marketed. The neglect of nonmarketed goods and services has long been recognized as a problem (see, for example, Antle and Capalbo, 1988). According to Gollop and Swinand (1998): "Because the consumption of water resources involves true opportunity costs no less than does the consumption of labor, capital, or material inputs, TFP measures must be viewed as biased barometers of how well society is allocating its scarce resources" (p. 577).[16] One of the conclusions of a review of agricultural productivity studies by Darku *et al*. (2013) was that future studies should make an effort to investigate the effects of irrigation and rainfall. Yet, according to Alston and Pardey (2014): "It is challenging to partition growth of agricultural productivity among different possible sources because the available data for many countries are very limited, especially for inputs…" (p. 129). Some authors now specifically mention that they were not able to account for the contribution of water as a separate input in TFP growth estimates because of a lack of appropriate data (for example, Wang *et al*., 2013).

Studies in two recent books by Alston *et al*. (2010a) and Fuglie *et al*. (2012a) on agricultural productivity patterns at the country, regional and global levels can be used to illustrate typical approaches for the inclusion of water aspects in TFP indices. For example, Fuglie (2010a), in a study on Indonesia,

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[16] With a slightly different perspective, Fuglie *et al*. (2012b) point out that it was increasingly recognized that future productivity gains in agriculture need to save not only land, but also a wider array of natural resources, such as water quantity and quality, so as to avoid negative impacts to the environment from agricultural intensification.

distinguished between irrigated and non-irrigated cropland. In an analysis of China's agricultural productivity, Jin *et al.* (2010) included irrigation costs among the material input costs. When examining the shifting patterns of agricultural productivity in the United States, Alston *et al.* (2010b) distinguished between irrigated and non-irrigated cropland, and added a miscellaneous input category to account for irrigation fees. Fuglie (2010b), in a study of TFP in the global agricultural economy using FAO data, divided cropland into rainfed cropland and cropland equipped for irrigation, and included irrigation fees in the cost share of agricultural land. Finally, Zhao *et al*. (2012), in an examination of annual TFP indices for Australia's broadacre agriculture[17] stated that an important reason for their significant fluctuations were variable climatic conditions, including the amount of moisture retained in the soil. These examples show that water aspects tend to be ignored in studies at national or higher levels. In some cases, irrigation water is indirectly considered through the area of land irrigated. Efforts are made to incorporate irrigation fees, but they may not approximate the price or opportunity cost of water. Not surprisingly, these studies do not provide any conclusions related to the effect of water on agricultural productivity patterns.

A few studies of TFP measurement at the subnational level, such as the provincial and district levels, do incorporate water aspects in more detail. For example, Murgai (1999) provided district-level TFP estimates for the Green and post-Green Revolution period in the Indian Punjab. By distinguishing between availability of canal irrigation and investments in private tubewells (and incorporating the former as an average monthly cost associated with the quantity of canal-irrigated area, and the latter as a cost item in the index of capital accumulation), she was able to identify the water source as an additional factor for the sharp differences in productivity growth across districts and cropping systems over time. Conradie *et al*. (2009) focused on South Africa's Western Cape Province and further disaggregated TFP indices for its regions and districts. They found that water availability (included as a dummy variable to indicate whether a district had a major river running through it) was an important explanatory variable. Districts with rapid TFP growth were those that not only showed water availability, but also the adoption of drip irrigation and a switch to export fruit production (which was made possible by a number of other factors, such as the introduction of an improved marketing system and cold storage facilities at the coast).

Besides TFP indices, frontier models are also frequently used in the agricultural production economics literature. The original frontier model was introduced by Farrell (1957) in a seminal paper that lays out a framework to measure economic efficiency, including technical efficiency which represents a firm's ability to reach the maximum potential output, given a given set of inputs and for a given technology; and allocative efficiency which captures the firm's ability to adapt optimally to market

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[17] Broadacre agriculture includes non-irrigated grains, beef and sheep production.

conditions, i.e. for each pair of inputs, the ratio of their marginal products equals the ratio of their market prices. Frontier models have been widely used in the agricultural economics literature over the past few decades. They encompass deterministic frontier models, stochastic frontier models (which are increasingly replacing the former), and DEA.

Bravo-Ureta *et al.* (2007) conducted a meta-analysis of frontier models with a focus on farm-level studies, including 167 articles for the period from 1979 to 2005. Their aim was to examine the effect of the studies' attributes on estimates of technical efficiency.[18] Results suggest, for example, that mean technical efficiency estimates of deterministic frontier models are lower than of those of stochastic frontier models, which in turn are lower than of those of DEA studies. Mean technical efficiency estimates were also examined by other factors, such as geographic region and farms' product type. Water issues are not mentioned. In order to shed light on the treatment of water aspects in this part of the productivity and efficiency literature, we reviewed the studies included in the meta-analysis[19] and found 28 studies with models that incorporated water. Yet most did so either by including water as one of numerous inputs, or by grouping water with other miscellaneous factors in a combined input. In both cases, water's role in technical efficiency was usually not analyzed further. Only six studies, briefly discussed below, incorporated water in more detail—including two DEA studies, three stochastic frontier model studies (with one of them also using a deterministic frontier model), and one study employing both DEA and stochastic frontier methods.

Among the DEA studies, Fraser and Cordina (1999) assessed the relative technical efficiency of a sample of irrigated dairy farms in an area of Australia where water was a constraining input. They aimed to demonstrate that DEA was a useful tool for benchmarking, and superior to the usual single-factor productivity measures, not least because it allowed the identification of influencing factors and of best-practice management that could then help in the design of extension programs. Irrigation water applied was one of the inputs considered for milk production. Results suggest that, for a given level of milk production, irrigation water applied could be reduced by about one-sixth if all farms operated efficiently. Another study by Sarker and De (2004) examined efficiency of paddy farms in different villages in West Bengal, India. They distinguished between 'technologically advanced' villages (with a high incidence of irrigation facilities and high yielding paddy varieties) and 'technologically backward' villages (with no irrigation facilities and traditional varieties). They find that the efficiency level between the two types of

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[18] A motivation for the study stemmed from the observation that the choice of method seemed to be largely arbitrary, owing to the objective of the study, the data available, and the researcher's own preferences.

[19] Of the 167 studies included in the meta-analysis, 158 studies were easily accessible and reviewed using the keywords "water", "irrigation", "irrigated", and "rain". Of the 158 studies, 44 mentioned at least one of the keywords. A further analysis showed that of these, 16 studies only mentioned one or more of the keywords but did not explicitly incorporate water aspects.

villages did not differ much, and conclude that the diffusion of new agricultural technology does not necessarily lead to a high level of efficiency. This would require other interventions such as technical training for farmers.

Among the stochastic frontier models, Ekanayake and Jayasuriya (1987) drew a distinction between rice farms depending on their location at the 'head' or 'tail' of a major irrigation canal in the Mahaweli Development Project in Sri Lanka. Farmers at the 'head' of the canal had access to irrigation water throughout the year, while access to water was more limited for farmers at the 'tail'. Comparing estimates from deterministic and stochastic frontier models, the authors find that farmers at the 'tail' experienced a high level of inefficiency in both models, but that the farmers at the 'head' show inefficiency only in the deterministic model. The latter result is attributed to pitfalls of the deterministic model, which does not allow the separation of random 'noise' from deviations arising from technical inefficiency. The authors conclude that inefficiency of farmers at the 'tail' is strongly correlated with water shortages, and that the stochastic frontier model is more suitable than deterministic procedures for measuring technical inefficiency.

Ali and Flinn (1989) started out by emphasizing that the traditional production function approach may not be appropriate if farms face different prices and have different factor endowments. Using farm-level data for Basmati rice producers in two Punjabi villages in Pakistan, one with better market access and lower transport cost than the other, they estimated farm-specific inefficiency via a profit frontier approach. They also identified sources of inefficiencies in order to design programs for increasing profitability. Among the factors included in the model were water constraints, mainly due to electric breakdowns, tubewell breakdowns, and unscheduled closure of canals. The authors find that water constraints cause profit losses, and recommend the establishment of workshops in the rural areas to help reduce down time due to pump breakdown through maintenance and timely repair.

Sherlund *et al.* (2002) used stochastic frontier modeling to examine the influence of omitted variables, such as environmental production conditions, on the measurement of technical efficiency. They use panel data for smallholder rice plots under rainfed conditions in Côte d'Ivoire, and apply two specifications for the model—one with and one without environmental variables. These variables comprise total rainfall and number of rainy days, and others such as soil and topographic characteristics. The findings show that properly accounting for heterogeneous environmental production conditions leads to much lower levels of estimated technical inefficiency, and more intuitive and precise estimates of its sources. The authors conclude that a bias in efficiency estimates from omitted variables may distort decisions on whether scarce resources should be spent on developing improved technologies or helping farmers to make better use of existing technologies.

Finally, Wadud and White (2000) compared technical efficiency estimates for rice farmers in Bangladesh employing a stochastic frontier model in combination with DEA, and found that inefficiency estimates are similar for both methods. They further analyzed technical inefficiency effects as a function of farm-specific socio-economic factors, environmental factors, and irrigation infrastructure (i.e. diesel-operated irrigation schemes). Results suggest that the inefficiency effects are positively influenced by the irrigation infrastructure. Electrification in rural areas would also be beneficial in reducing technical inefficiency.

Beyond reviewing the studies included in the meta-analysis of Bravo-Ureta *et al.* (2007), we also searched for further applications of frontier models to issues related to agricultural water management.[20] We found three more recent studies, two of which focused on rice farms in Asia and the third on smallholder plots in Ethiopia. Yao and Shively (2007) used panel data for a sample of rice farms in the Philippines over a period when they transitioned from rainfed to irrigated production. A time-varying stochastic frontier model was applied to examine technical efficiency within the context of technical change (i.e. irrigation development). A dummy variable captured whether a given parcel was irrigated during the dry season. The authors find that irrigation was correlated with gains in efficiency vis-à-vis rainfed production. They also find that efficiency was lowered by the distance to irrigation canals, and by problems with siltation of irrigation canals. Thus, the management of irrigation water appears to play a crucial role in influencing technical efficiency.

Gedara *et al.* (2012) used a stochastic frontier model to investigate the factors affecting technical efficiency of rice farms relying on village reservoir irrigation systems in a district in Sri Lanka. The irrigation networks operate on a rotational delivery system based on allocation decisions made by the village's farmer organization. Water use was assumed to be proportional to the farm area cropped, and variation in the individual use of water was captured by including irrigating time (i.e. the time the water flowed over the land in minutes). The position in the system (e.g. head, middle or tail-end) was also included. The authors find that rice production could increase by 28 percent without increasing other inputs and using current technologies. Encouraging membership in farmer organizations and collective actions organized by them could contribute to efficiency improvements.

Gebregziabher *et al*. (2012) compared the technical efficiency of irrigated and rainfed smallholder plots in Tigray, Ethiopia with a stochastic frontier model. Referring to Sherlund *et al.* (2002) who noted that the omission of environmental production variable may lead to an upward bias in the estimated technical inefficiency, they used propensity score matching to select rainfed plots that were

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[20] The search was carried out in the database EconLit using the terms "stochastic frontier", "deterministic frontier" or "data envelopment analysis", combined with the terms "irrigation", "water" or "rain" in the title.

similar in characteristics to irrigated plots. Their findings indicate that irrigated agriculture had a large potential to improve technical efficiency which could be supported by, for example, farmer training in irrigation agronomy and on-farm water management. Rainfed agriculture seemed to produce close to its production frontier, and improving soil moisture would be a measure for shifting the production frontier upward.

We also found two earlier studies not included in the meta-analysis of Bravo-Ureta *et al*. (2007) that applied stochastic frontier modeling to irrigated farms: McGuckin *et al*. (1992) and Karagiannis *et al.* (2003). These two studies are of particular interest for our purpose because they emphasize the importance of distinguishing between irrigation efficiency (as used in the irrigation engineering literature) and economic efficiency involving technical and allocative efficiency [with Karagiannis *et al*. (2003) referring to Mc Guckin *et al*. (1992) as well as Farrell (1957)].[21] Irrigation efficiency is only one dimension of input use; it is a physical measure of the irrigation technology assuming a level of management—while technical and allocative efficiency are measures of management capability.[22] Both studies also include irrigation water as a continuous variable (in terms of water applied), and are concerned with farmers' irrigation water savings. However, the "water savings" discussed are in the form of reduced water applications, not consumption—and therefore potential externalities beyond the farm level in terms of return flows were not explicitly considered.

McGuckin *et al*. (1992) used farm observations for corn producers in a homogeneous crop region of Nebraska, United States, who applied groundwater by gravity or sprinkler systems as supplemental irrigation. The frontier was estimated as a Cobb-Douglas model of irrigation (in terms of water applied)—with soil conditions, rainfall and irrigation technology included as exogenous variables that shift the frontier, and all other inputs excluded. The authors hypothesize that technical inefficiency of irrigation depends on available field information (e.g., soil moisture monitoring, commercial scheduling and/or weather reports). Their findings indicate that information on field conditions from moisture sensors is a particularly important factor for improving technical efficiency of irrigation practices.

Karagiannis *et al.* (2003) specified a stochastic production frontier model to measure irrigation water efficiency (in terms of water applied) on farms with out-of-season (greenhouse) vegetable cultivation in Crete, Greece. To start out, they proposed to define irrigation water efficiency not along the

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[21] As noted in section 2, Seckler (1996) also started out with a critique on the usefulness of the term irrigation efficiency for guiding water management decisions (especially at the basin level) but—unlike McGuckin *et al*. (1992), and citing them, Karagiannis *et al.* (2003)—did not elaborate on the relationship between irrigation efficiency and economic efficiency.

[22] As McGuckin *et al.* (1992) put it: "Compared to a furrow system, a sprinkler irrigation system could reduce water use and increase irrigation efficiency but at the expense of an increase in capital. With very low cost water, the sprinkler would be allocatively inefficient. More subtly, a sprinkler could also be technically inefficient. With improved management, a sprinkler system might use as much water as the furrow system and thus be technically inefficient compared to the well-managed furrow system" (pp. 306-307).

lines of the engineering-oriented concept of irrigation efficiency; instead they use the concept of water-specific technical efficiency, defined as "the ratio of the minimum feasible water use to observed water use, conditional on the production technology and observed levels of output and other inputs used" (p. 58). The cost saving related to the adjustment of irrigation water to a technically efficient level—while holding all other inputs and output at observed levels—will vary with prices, and "relatively inefficient water use in a physical sense can be relatively efficient in a cost sense, and *vice versa*" (p. 60). Thus, while the measures of output-oriented and input-oriented technical efficiency do not identify the efficient use of individual inputs, "water-specific technical efficiency" is an input-oriented single factor measure that provides information on how much water use could be decreased without altering the output produced, the technology (including the irrigation technology) utilized, and the quantities of other inputs used. Empirical results indicate that water-specific technical efficiency is on average much lower than output-oriented technical efficiency, indicating that farmers could become significantly more efficient in irrigation water use, given the present state of technology and input use. Furthermore, modern greenhouse technologies, education and extension are the main factors associated positively with the degree of water-specific technical efficiency.

5. Deductive Methods

While the agricultural productivity and efficiency literature mostly relies on TFP indices and frontier models, deductive methods are an important part of the agricultural and (irrigation) water economics literature and have been applied extensively since the 1960s. Similar to TFP indices and frontier models, deductive methods belong to the category of multi-factor approaches. They are highly flexible with regard to scale, and can be applied from field, farm, irrigation system to the basin level and the national level, sometimes in combination with other methods. Thus, in contrast to TFP indices and frontier models, they can account for externalities such as return flows.

An illustration of the deductive method is provided by Eckstein (1958). Examining practices for evaluating irrigation project development, he illustrates the role of a with-and-without (irrigation water) approach employing farm budgets and assumed crop output prices to deduce project benefits. The example, from standard U.S. Bureau of Reclamation practice, illustrates the estimate of water value as a residual: that is, the remaining value after crop production expenditures have been subtracted from crop revenues. If this residual is positive, then standard benefit cost interpretations would infer a socially beneficial outcome from pursuing the project. The method provides explicit expectations of crop outcomes and yields, together with the required water storage, conveyance, application, and related non-water inputs.

This illustration of the deductive method through the use of residual imputation (Young, 2005) focuses on farm level production when one new input, irrigation water, is added. A more general understanding of the role of irrigation water in agricultural production can be obtained by incorporating a broader range of specific technologies (e.g. fertilizer use and irrigation technology). A crop budget typically is prepared for every crop and technology combination, with each serving as the basis for an activity in a mathematical programming (optimization) problem.[23] When solved for a variety of water supply levels, model solutions can provide cropping mix, production, and irrigation technology use for each water supply level. Alternatively, different water prices can be used to generate cropping and production patterns.[24]

Early examples of a linear programming models employing this approach include Hartman and Whittlesey (1961), and Moore and Hedges (1963) who model farms of various sizes with 54 production activities representing combinations of alternative crops, irrigation treatments, and soil grades. Yaron (1967) introduces activities representing flexible irrigation practices. Heady *et al* (1973) demonstrated the use of linear programming to address such fundamental issues as the use of water resources in meeting future economic development needs, and the ability to substitute between water, land, and other inputs in agricultural production. The study encompassed over 200 land regions, and 51 water supply regions in the United States. Heady *et al*. demonstrated the possibility of modeling the impact of factors including water prices, population, farming technology, exports, and agricultural policies on regional and national agricultural production.

These early linear programming studies illustrate the use of deductive methods based on the residual imputation of the difference between gross crop revenue and opportunity costs of all other inputs. Typically, constant output prices are used, raising questions of applicability particularly during periods of acute water stress or potential output disruptions. Allowing crop prices to depend on output can be accommodated, and is demonstrated in the quadratic programming model used by Howitt *et al*. (1980) in estimating agricultural production and short-run irrigation water use in 14 regions of California.[25]

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[23] Each crop budget is implicitly assumed to be at the production frontier and thus technically efficient. Moreover, the fixed proportion of inputs in the crop budget is presumed to represent allocatively efficient input usage.

[24] With regard to residual imputation, it needs to be noted that it relies by its nature on finding meaning in the difference between project benefits (usually revenues) and costs (typically dominated by crop production costs). Because benefits and costs are uncertain, and the difference between benefits and costs is typically small compared to their level, estimates of the difference (the residual) have a much higher level of uncertainty. It is easy to neglect this underlying factor when interpreting the very detailed and extensive output from typical mathematical programming models.

[25] A particular challenge across mathematical programming approaches is the problem of calibration. Naïve mathematical programming models rarely result in solutions which reflect observed crop distributions or technology choices under representative water supplies and output prices. This is typically ascribed to a myriad of producer constraints and hidden costs which are not evident to the modeler. This problem is often handled with a series of ad hoc constraints on crop acreages. Another response, proposed and implemented by Howitt (1995), is to recognize the existence of unobserved costs and

Deductive methods can be used to incorporate the linkages among water users, such as those illustrated in Figure 3. The impact of these physical externalities on other water users, including other agricultural producers, is critical to the question of improving agricultural water productivity under water scarcity. Deductive methods can also incorporate the various economic linkages created by agricultural production. The relationship of these linkages, and economic activity in upstream and downstream sectors, is both important and contentious as they relate to water use in irrigated agriculture.

Physical linkages between water users are treated by what Harou *et al.* (2009) term hydroeconomic models. They are particularly useful for addressing regional water development and allocation questions where the use of regional water resources is best treated as an integrated set. This is critical in understanding, for example, the impacts of increasing irrigation efficiency through new, more capital-intensive irrigation technology. While water withdrawals are likely to decline, consumptive use and hence regional water depletion may actually increase, as demonstrated in theory (Huffaker and Whittlesey, 2003) and in mathematical programming models (Scheierling *et al*., 2006; and Ward and Pulido-Velazquez, 2008). More generally, hydroeconomic models seek to incorporate the notion that regional water analysis typically includes a variety of interconnections (e.g. one user's return flows are the next user's supply), including those between ground and surface water. For example, Bredehoeft and Young (1970) demonstrate intertemporal opportunities for improved irrigation outcomes in a linked stream-aquifer system where producers can draw from both ground and surface water. A review of approaches based on deductive methods which link hyrdroeconomic models to policy is provided by Booker *et al.* (2012). The explicit treatment of return flows as an externality is addressed by Taylor *et al*. (2014), while Letcher *et al*. (2006) provides an example for the explicit consideration of the impacts of dry-season irrigation use on deforestation, erosion, and surface water quality in a catchment in Thailand.

A common element of ecohydrologic models is typically the inclusion of key physical linkages between potential water users such that changes in diversions and consumptive water uses are fully accounted for in the resulting water (surface and ground) flows and stocks. But these models are often partial equilibrium models from an economic perspective: linkages with key related economic sectors (e.g. labor markets) are likely to be absent. Mathematical programming approaches can be linked with input-output analysis to estimate potential impacts on downstream economic activity as agricultural production is affected by changes in water supplies (see, for example, Gunter *et al*., 2012). But general equilibrium approaches are needed to include feedback to agricultural markets (e.g., changes in input

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incorporate these into a self-calibration procedure. A helpful application of this approach, called positive mathematical programming, is provided by Medellin-Azuara *et al.* (2009).

costs) from macroeconomic linkages. Roe *et al*. (2005) provide a clear discussion of the issues, and an application of such a computable general equilibrium (CGE) model.

6. Discussion and Conclusions

When looking for water in the agricultural water productivity and efficiency literature, it becomes apparent that many studies have examined the question of agricultural water productivity from various perspectives. The irrigation literature, on the one hand, is dominated by studies using single-factor productivity measures. They allow the incorporation of different measures of water use (such as water applied and water consumed) and various scales, ranging from the field to the basin and even global levels. They find large variations in agricultural water productivity, yet usually do not proceed to empirically investigate the factors that might explain the different findings. The use of such single-factor productivity measures, where all variations in output are attributed to the water input, is problematic—especially when they form the basis of policy recommendations for improving agricultural water productivity. These measures disregard the effects of linkages with other inputs (including environmental influences), do not incorporate prices or costs, and do not consider the different sources of productivity.

The agricultural economics literature on productivity and efficiency, on the other hand, has relied on inductive methods, such as TFP indices and frontier models. As multi-factor approaches, these methods avoid some of the key problems of single-factor productivity measures, but have their own shortcomings when it comes to incorporating water aspects and providing insights into how water could be used more productively. TFP studies at the national level tend to not include water as a separate input, often due to data problems. A few TFP studies at subnational levels, such as the district level, capture water aspects as dummy variables and may show, for example, that water availability (in connection with other factors) is an important input associated with TFP growth.

The frontier model studies examined here tend to be based on farm level data and focus mostly on technical efficiency. With a few exceptions, they include water aspects only in qualitative form as dummy variables. Most of the studies examine the extent of inefficiency as well as the significance and magnitude of the factors that may be causing the inefficiency. Depending on the particular case, the problem analyzed, and the approach used, they find that water aspects (such as water availability, irrigation infrastructure, farms' location along a canal, or farmers' water management arrangements) play different roles in terms of efficiency. Two frontier model studies, by McGuckin *et al*. (1992) and Karagiannis *et al*. (2003), stand out: they specifically examine irrigation water efficiency in economic terms, and try to estimate potential water savings. However, both studies are limited in that they only consider one measure of water use at the farm level, water applied, and assume that any reduction in this measure would constitute a decrease in water "waste" and thus a water saving. As outlined in Section 2, this is not necessarily the case in the context of a basin where return flows are important for downstream users—even if irrigation water efficiency is considered in economic, instead of in engineering, terms.

Overall, our review suggests that most studies presented in the agricultural productivity and efficiency literature, and employing inductive methods, either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multi-factor approach but do not tackle the basin-level. Based on this first, albeit partial, review of the literature, it seems that no study on agricultural water productivity has yet presented an approach accounting for both multiple inputs and basin level issues.

Deductive methods—while, strictly speaking, not part of the agricultural productivity and efficiency literature, but often applied in irrigation water economics—offer some hope of addressing the shortcomings of the inductive methods. While not inherently equipped with a multi-factor, basin-level framework, deductive methods do provide the flexibility to overcome many of the limitations of the other methods.

Concluding, while the need to improve agricultural water productivity is widely emphasized in reports and public communications, its meaning often remains ill-defined. This survey of the agricultural productivity and efficiency literature—to our knowledge the first of its kind—indicates that there is an abundance of studies applying a wide range of definitions and methods (and also advocating a wide range of interventions), but it seems that no single approach has yet been able to tackle the complexity of the various aspects of agricultural water productivity. Going forward, it will be important to achieve progress on several fronts. Since water productivity improvements in agriculture may mean many different things, studies should lay out much clearer the objectives they are pursuing in a particular case and be more transparent about their respective limitations, especially if partial approaches are being pursued. Efforts to gather more data on the different measures of agricultural water use need to intensify, even though the special characteristics of water makes this a more difficult and costly endeavor compared to most other factors involved in the agricultural production process. And, last but not least, more intensive collaboration between the various concerned disciplines may well help to arrive at more comprehensive approaches.

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