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Water Productivity in Agriculture: Looking for Water in the Agricultural Productivity and Efficiency Literature

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Expectations are that the agricultural sector will have to expand the use of water for irrigation to meet rising food demand, while at the same time the competition for water resources is growing in many regions. Increasing water productivity in agriculture is widely seen as a critical response to help address this challenge. Yet much of the public debate is vague on the meaning of agricultural water productivity — often emphasizing "more crop per drop" as if water were the only input that mattered —, and approaches for assessing and increasing water productivity are seldom addressed systematically. This paper discusses conceptual issues that should be kept in mind when assessing agricultural water productivity, and presents findings from what may be the first survey of the agricultural productivity and efficiency literature with regard to the explicit inclusion of water aspects in productivity and efficiency measurements. The survey comprises studies applying single-factor productivity (SFP) measures, total factor productivity (TFP) indices and frontier models. Studies using deductive methods are also included. A key finding is that the studies tend to either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply multi-factor approaches but do not tackle the basin-level aspects. It seems that no study has yet presented an approach that accounts for multiple inputs and basin-level issues. Deductive methods may provide the flexibility to overcome some of the limitations of the other methods.

Keywords: Agricultural water productivity; irrigation efficiency; single-factor productivity; total productivity; frontier models; deductive method.

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1. Introduction

It is increasingly acknowledged that without advances in water management and more integrated policy making in both developed and developing countries, water-related problems will significantly worsen over the next several decades (World Water Assessment Program 2012; World Economic Forum 2015). Among the key factors influencing this situation are water management issues in the agricultural sector. Agriculture is by far the largest user of water, with irrigated agriculture accounting for about 70% of total freshwater withdrawals worldwide (Molden 2007). Water use in agriculture also tends to have relatively low net returns as compared to other uses. As water becomes scarcer, other users tend to turn to agriculture as a potential source of water (Young 2005). At the same time, it is expected that the agricultural sector will have to expand the use of water for irrigation due to continued population growth, rising meat and dairy consumption, and expanding biofuel use. Projections indicate that agricultural production in 2050 would have to be 60% higher than in 2005/2007 and irrigation water withdrawals would need to increase from 2,761 km^3 to 2,926 km^3 to meet the likely demand (Alexandratos and Bruinsma 2012). In many parts of the world, the availability of irrigation water may become a major factor in this regard, especially when the impacts from climate change are taken into account (World Bank 2012).

In order to help address these challenges, it is often recommended that efforts should focus on improving water productivity in agriculture (Seckler 1996; Jury and Vaux 2005; UNESCO 2009; FAO 2012; World Bank 2013). Given the large amounts of water involved, and the widely held perception that water use in agriculture is relatively inefficient, even small improvements in agricultural water productivity are believed to have large implications for local and global water budgets. Such improvements would allow either higher agricultural production with the same amount of water or the same amount of agricultural production with less water. In the latter case, the water savings could be reallocated to other higher-value uses, or freed up to ensure some level of environmental flows.

Yet much of the public debate uses the term agricultural water productivity 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 input that mattered.[1] Partly due to this lack of a clear conceptual framework, approaches for assessing and

[1]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).

increasing water productivity and/or efficiency are seldom systematically discussed. Moreover, the aims to which these approaches are to contribute, such as agricultural expansion or water conservation and/or reallocation, are often not spelled out.

Nevertheless, in both developed and developing countries large public and private investments are being made for increasing agricultural water productivity. A popular intervention is the provision of support to farmers for switching to more capital-intensive on-farm irrigation technologies to increase the "efficiency" of irrigation water use. For example, the US Department of Agriculture has long provided such assistance, including under the Environmental Quality Incentives Program. Since 1997, subsidy payments of about US$ 1 billion have been made under this program to help farmers buy more capital-intensive irrigation equipment, such as sprinklers and pipelines, with the aim to save water (New York Times 2013). The common presumption that the adoption of improved on-farm irrigation technologies would provide water savings for alternative uses has not gone unquestioned (Scheierling *et al.* 2006). Some early water economists such as Hartmann and Seastone (1965) pointed out that only part of the water withdrawn from a river, and applied to a farm field, is used consumptively,[2] with the remaining part typically returning to the river as runoff or percolating into the underlying aquifer. Based on a simplified river system, they illustrated that any change in these return flows, such as from the transition to an improved irrigation technology, may affect downstream users. Subsequent studies based on normative models showed that such transitions are likely to reduce on-farm water applications but may also increase them in some circumstances (Caswell and Zilberman 1986; Huffaker and Whittlesey 2003; Peterson and Ding 2005). In the case of the Environmental Quality Incentives Program, econometric estimates indicated reductions in water application rates and, concomitantly, an increase in water use and an expansion in irrigated area (Wallander and Hand 2011). Further studies showed that even if subsidies for improved irrigation technologies result in less water being applied, they are unlikely to led to a decrease in consumptive use and thus do not provide real water savings (Scheierling *et al.* 2006; Huffaker 2008; Ward and Pulido-Velasquez 2008; and Frisvold *et al.* 2013). Especially in river basins where

[2]It is useful to distinguish among these three measures of water use: water withdrawn, water applied, and consumptive use. Withdrawal measures the amount of water removed from a surface or ground water source. Water applied differs from water withdrawn by the amount of water lost in transit from the point of withdrawal to the point of delivery. Consumptive use (or evapotranspiration) is the amount of water that is actually depleted by the crops, i.e., lost to the atmosphere through evaporation from plant and soil surfaces and through transpiration by the plants, incorporated into plant products, or otherwise removed from the immediate water environment.

return flows are important, improved irrigation technologies would mainly redistribute basin water and potentially harm users dependent on return flows. They may even led to an increase in consumptive use, especially if farmers can expand irrigated acreage.

In this paper, we argue that many of the complexities in the discussion about assessing and increasing agricultural water productivity and efficiency are related to two key issues: The first is the unique characteristics of water. Because of its mobility, exclusive property rights for water are relatively difficult and expensive to establish and enforce (Young 2005). Furthermore, as first illustrated by Hartmann and Seastone (1965), water is rarely completely consumed in the course of its "use". In crop production, it is not unusual to find that 50% or more of the water withdrawn from a water source is returned to the hydrologic system in the form of return flows, with the quantity, quality and timing of return flows affecting downstream users in many cases. These physical externalities make it 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.

The second issue is the multi-disciplinary nature of the topic. Among the disciplines involved are hydrology and hydrogeology, civil and irrigation engineering, agronomy and crop physiology, and economics. Each discipline tends to understand the terms productivity and efficiency in a different way, and also focus on different measures of water. Even within disciplines, various productivity and/or efficiency terms are used or newly coined depending on the focus of study and the approach employed. Some key terms and their common definitions are presented in Table 1. In civil engineering, for example, conveyance efficiency (the ratio of the water received at the farm gate relative to the water withdrawn from a water source) is an important term. In irrigation engineering, application efficiency (the ratio of the water stored in the root zone, and ultimately consumed, relative to the water delivered to the farm) and irrigation efficiency (the ratio of the water consumed relative to the water applied or withdrawn) are classical concepts (Israelsen 1950; Jensen 2007). Agronomists and crop physiologists often use the term water use efficiency, and apply different definitions (such as the ratio of plant biomass or yield relative to transpiration or water consumed (Hsiao *et al.* 2007).

In the irrigation literature, such efficiency terms have dominated the discussion for many decades. Productivity measures have only become more widely used after Seckler (1996) pointed out that local improvements in irrigation efficiency (for example, by switching to more capital intensive irrigation technologies at the level of the farm or irrigation system) may not lead to real water savings nor translate into basin-wide efficiency gains, and recommended to focus on water productivity in irrigated agriculture instead — but without further defining the

Table 1. Key Water-related Efficiency and Productivity Terms in the Irrigation Literature

Term	Definition	Discipline
Conveyance Efficiency	Ratio of the water received at the farm gate relative to the water withdrawn from the water source (Jensen 2007)	Civil Engineering
Water-Application Efficiency	Ratio of the water stored in the root zone (and ultimately consumed) relative to the water delivered to the farm (Jensen 2007)	Irrigation Engineering
Classical Irrigation Efficiency	Ratio of the water consumed relative to the water applied or withdrawn from a source (Israelsen 1950; Jensen 2007)	Irrigation Engineering
Water Use Efficiency	Ratio of the plant biomass or yield relative to transpiration or consumptive use (Molden 1997; Hsiao *et al.* 2007)	Agronomy and Crop Physiology
Water Productivity	Ratio of physical production or "economic value" of production (in terms of gross or net value of product) relative to water use (in terms of water withdrawn, applied or consumed) (Molden 1997)	Agronomy and Crop Physiology

term. Subsequently, many different definitions have been suggested and applied, mostly along the lines of "crop per drop" — and thus similar to definitions of water use efficiency in agronomy (Molden 1997).

In the economics literature, particularly in agricultural production economics, productivity and efficiency aspects are defined in different ways. The productivity of a firm is defined as the ratio of its output to its input, and the efficiency is a comparison between observed and optimal values of its output and input (Fried *et al.* 2007). The analysis is carried out with a range of methods. Following Ruttan (2002), three groups of methods can be distinguished: single-factor (or partial) productivity (SFP) measures, total factor productivity (TFP) indices, and frontier models. SFP measures relate output to only one input, and are relatively easy to calculate. Early on, the production economics literature pointed out that SFP ratios or indices are affected by the intensity of use of the excluded inputs.[3] Therefore,

[3]For example, Heady and Dillon (1961, p. 590) 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".

they give an incomplete picture of the underlying drivers of productivity change, especially when used in isolation. Furthermore, they are not marginal, but average products (Wichelns 2014). They also do not account for the possibility of input or output substitution (Latruffe 2010).

Because of these limitations, the economics literature on agricultural productivity and efficiency mainly employs the other two groups of methods, TFP indices and frontier models (Coelli *et al.* 2005). TFP indices are particularly concerned with the incorporation of all inputs of the production process.[4] They compare a single output or an aggregate output index to an aggregate input index, with different ways of aggregation leading to different TFP indices. The indices require quantity and price information for the outputs and inputs included, and assume implicitly that all firms are efficient. TFP changes over time are attributed to technological change. The third group of method, frontier models, measures 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 (Latruffe 2010). Parametric methods rely on specifying a production frontier and estimating its parameters econometrically, with deterministic frontier analysis assuming that any deviation from the frontier is due to inefficiency, and stochastic frontier analysis also allowing for statistical noise.[5] 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).

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 methods, and includes residual imputation methods, mathematical programming, hydro-economic models, and computable general equilibrium (CGE) models. They are often based on "representative farm models" that can portray a farm scenario or aggregate a regional total, and incorporate producers' resources (including water

[4]Because of the difficulty of capturing all inputs (and outputs) that interact in the production process, TFP indices are also referred to as multi-factor productivity indices.

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

and all other inputs) and technological options based on realistic assumptions about productivity of resources, market availability, and managerial capability. Deductive methods usually do not focus on inefficiencies, but can take into account technological change. They can be constructed to reflect any future economic and technological conditions, which makes them useful for policy analysis and project planning.

This paper aims to contribute to the increasing debate on agricultural water productivity on two fronts: First, by discussing conceptual issues that should be kept in mind when assessing water productivity in agriculture and, second, by presenting findings from a survey of the agricultural productivity and efficiency literature that explicitly includes water aspects in productivity and efficiency measurements. To our knowledge, this is the first attempt to undertake a review and analysis of this type. The focus is on studies that apply SFP measures, TFP indices or frontier models that incorporate water aspects. Studies using deductive methods are also included. Given the extensive literature on agricultural productivity and efficiency, the survey does not attempt to be exhaustive. A key finding is that water-related studies presented in the agricultural productivity and efficiency literature tend to either incorporate field- and basin-level aspects but focus only on a single input (water), or apply a multi-factor approach but without incorporating basin-level aspects. Deductive approaches may provide the flexibility to overcome some of these limitations. The remainder of the paper is organized as follows. Conceptual issues are further elaborated in Section 2. They provide a framework to the literature survey in Section 3. Section 3.1 reviews studies with SFP measures, mostly from the irrigation literature. Section 3.2 examines studies with multi-factor approaches, comprising TFP indices and frontier models, from the agricultural production economics literature. Deductive methods from the irrigation water economics literature are presented in Section 3.3. This is followed by Section 4 with a discussion and conclusions.

2. Conceptual Issues

Our discussion of conceptual issues focuses on a number of dimensions that need to be considered when assessing agricultural water productivity, but tend to be neglected when the emphasis is on a simple ratio such as "crop per drop". We start out with a brief exposition of the definitions of efficiency and productivity in economics, and of the sources of productivity increases. Figure 1 shows a single input–single output case ($Y = f(X)$), with X representing the water input, Y crop yield, and f the production frontier. Initially the firm operates at point A. Productivity may improve through (i) increased technical efficiency, i.e., the same

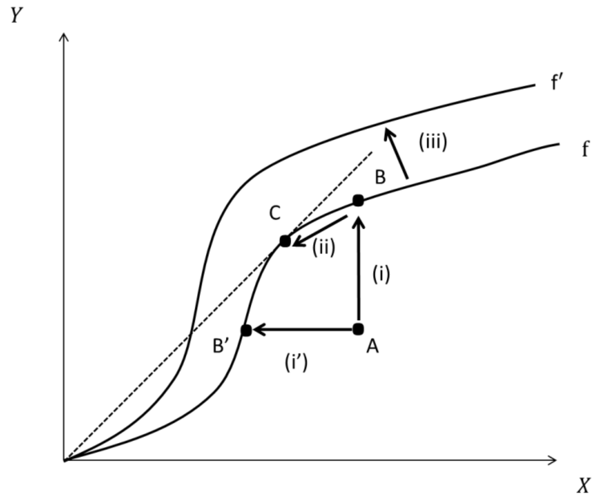


Figure 1. Sources of Improvements in Productivity

Source: Coelli *et al.* (2005).

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 (and a behavioral assumption) are also included in the analysis, allocative efficiency as another source of productivity change can be considered. In input selection, this would involve selecting that mix of inputs that provides a given quantity of output at minimum cost.

A ray through the origin in Fig. 1 has the slope y/x and thus provides a measure of average productivity, as in the SFP measure "crop per drop". More crop per drop could be achieved by any of the moves described above. Thus, even in the single input–single output case, an increase in that ratio could be the result of different sources, and be associated with less or more water use; without further analysis, these underlying causes would not be obvious.

Crop per drop ratios are also affected by the different water measures such as water withdrawn, water applied, and water consumed. Depending on which measure is represented on the *X*-axis of Fig. 1, the crop per drop ratios may differ. Figure 2 further illustrates this issue, including how the different ratios may change as a result of an intervention such as the switch to a more capital-intensive irrigation technology.[6] 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% 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%. 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. Depending on the underlying water measure in the crop per drop ratio, the values for agricultural water productivity range from 1.0 to 2.8.

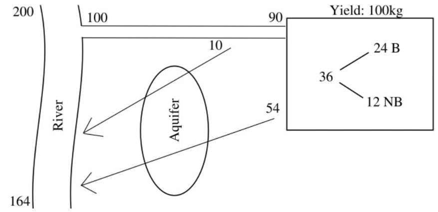
Case (ii) shows the effects from an improvement in on-farm irrigation efficiency from 40% to 60% (because the farmer moved to a more capital-intensive irrigation technology, for example, from a gravity system to sprinklers). Water application could then be reduced from 90 m^3 to 60 m^3, and withdrawals from 100 m^3 to 67 m^3. The respective crop per drop values increase significantly.[7] Yet because water consumption does not change[8], 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. In case (iv), additional interventions beyond the increase in irrigation efficiency (such as improved agronomic practices) are made to achieve real water savings while not affecting yields. The beneficial consumption of 24 m^3 necessary for crop growth remains the same as in the cases (i) and (ii), but the non-beneficial consumption is reduced by two-thirds

[6]Similar illustrations were presented in Hartmann and Seastone (1965), Huffaker and Whittlesey (1995), and Huffaker and Whittlesey (2000), though without a focus on ratios of agricultural water productivity. The numbers used in the illustrations are not intended to represent a real-world irrigated area or river basin.

[7]In terms of the framework presented in Fig. 1, with the *X*-axis representing water withdrawn or applied, this increase would be 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).

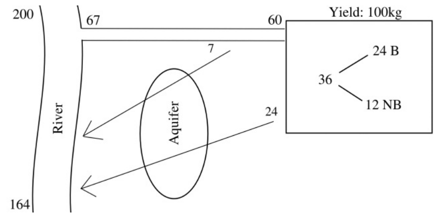
[8]With constant crop yield, a constant level of water consumption is assumed regardless of the level of water application. This assumption is also made in the following cases.

Case (i): 40% Irrigation Efficiency



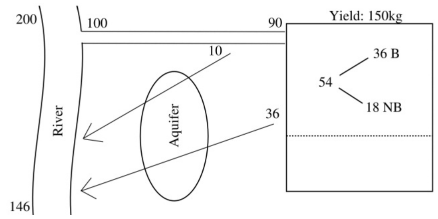
	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	100	1.0
Applied	90	1.1
Consumed	36	2.8

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



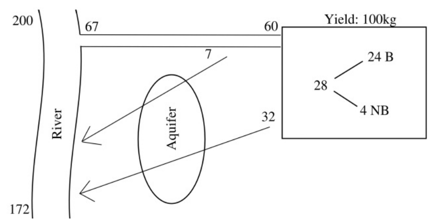
	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.8
Consumed	36	2.8

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



	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	100	1.5
Applied	90	1.7
Consumed	54	2.8

Case (iv): 60% Irrigation Efficiency, No Water Spreading, Reduction of Non-Beneficial Consumptive Use (NB) by 66%



	Water Measure (m^3)	Crop per Drop (kg/m^3)
Water		
Withdrawn	67	1.5
Applied	60	1.7
Consumed	28	3.6

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

(from $12\,m^3$ to $4\,m^3$) as a result of the additional interventions. Real water savings amount to $8\,m^3$. The crop per drop values for water withdrawn and water applied are the same as in cases (i) and (ii), but the crop per drop value for water consumed increases.

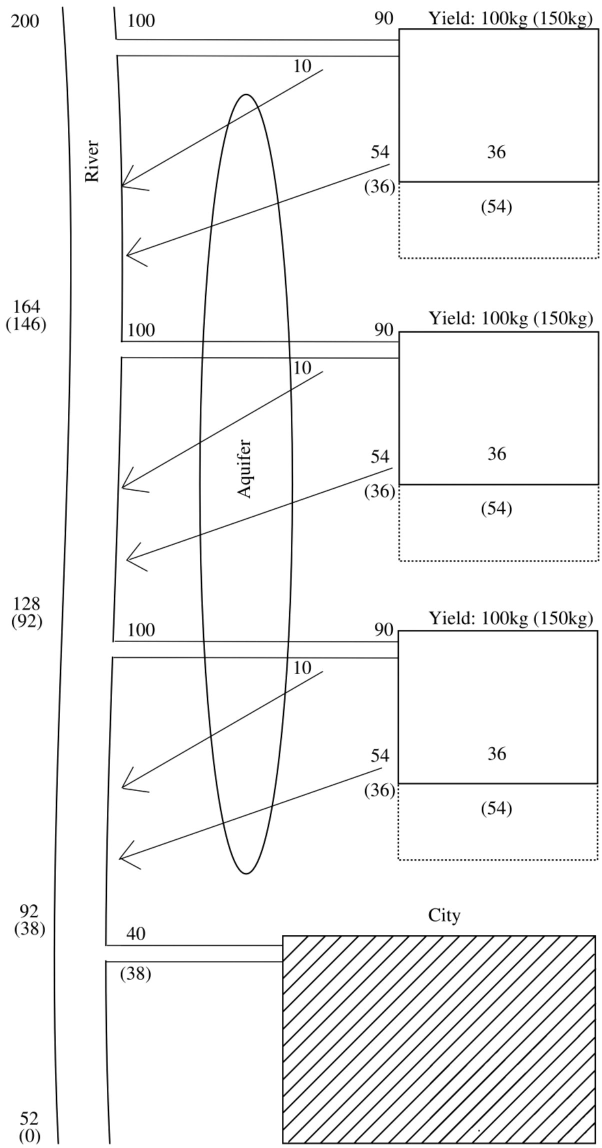


Figure 3. Basin-Wide Effects of an Increase in On-Farm Irrigation Efficiency from 40% to 60% with Water Spreading (in Brackets)

Going beyond the field level, Fig. 3 shows a basin with several water uses. Building on cases (i) and (iii) of Fig. 2, two additional irrigated areas with similar features and a city requiring 40 m^3 of water consumption are now assumed to be located downstream. Initially, as in case (i), the three irrigated areas operate with an on-farm irrigation efficiency of 40%, with each producing 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^3 which would be considered sufficient for environmental purposes. If, as in case (iii), the irrigated areas switch to an on-farm irrigation efficiency of 60% and continue to withdraw the same water amounts (because the water rights are formulated in terms of withdrawals, for example), they can spread the water on more land and increase their combined yield from 300 kg to 450 kg (shown in brackets in Fig. 3). 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 agronomic 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 illustrating some of the limitations of crop per drop ratios as productivity measures at the field and basin levels, Figs. 2 and 3 are based on a conceptual framework that suffers from three shortcomings: only one input (water) is considered; productivity increases stem only from technological progress, with possible efficiency gains not being considered; and prices are not included. Figure 4 strives to address these shortcomings by using a multi-factor framework that also allows for a discussion of the concepts of technical and allocative efficiency. It represents the situation where a farmer, originally at point A, produces a given crop in the quantity Y 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.[9] 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 while keeping the 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. Taking into account the prices of inputs, the farmer could strive to be efficient from an allocative point of view,

[9]Other inputs, denoted as X in Fig. 4, are assumed to be 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.

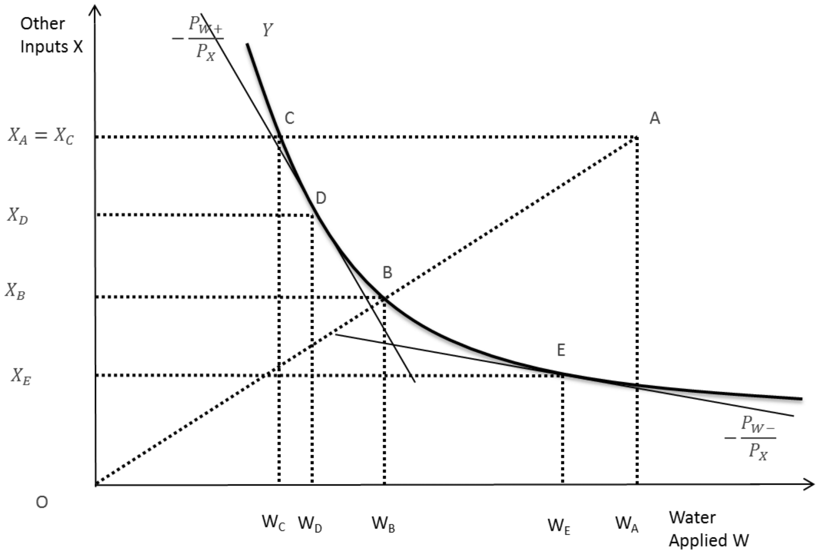


Figure 4. Effects of Input-Oriented Technical Efficiency, Water-Specific Technical Efficiency, and Allocative Efficiency on Water Applied and Other Input Use

reaching a level of water applied of W_E or W_D (with $W_E > W_D$) depending on the price of water, P_{W-} or P_{W+} (with $P_{W-} < P_{W+}$), respectively.

More generally, points such as D and E represent an allocatively efficient use of water and other inputs contingent on the ratio of the prices of water and the other inputs. According to standard production theory, least cost production of outputs Y is achieved when the ratio of the marginal products of water and the other inputs equals their price ratio $(\text{MP}_W/\text{MP}_X) = (P_W/P_X)$ for any point (or combination of inputs) on the isoquant, with P_W and P_X giving the full opportunity costs of using water and the other inputs, respectively. The marginal product of water can then be written as $\text{MP}_W = (P_W/P_X)\ \text{MP}_X$. This implies that an SFP measure for agricultural water productivity, when expressed not as an average product as in "crop per drop" but as a marginal product, should be expected to be high when the price of water is high, the cost of other inputs is low, and the marginal product of the other inputs is high.[10]

Overall, the illustrations presented in Figs. 1–4 provide insight into some of the key issues that the water-related studies in the agricultural water productivity and efficiency literature seek to address. The survey of the literature below starts out

[10]It is important to note that the focus in Fig. 4 is on water applied, and return flow issues are neglected. The latter are dealt with in more detail in Scheierling *et al.* (2014).

with a look at the irrigation literature, followed by the agricultural production economics literature.

3. Water in the Agricultural Productivity and Efficiency Literature

3.1. *Single-factor approaches: SFP measures*

The use of SFP measures is dominant in productivity-related studies in the irrigation literature. Its origin can be traced to Seckler (1996). Other authors, many associated with the International Water Management Institute (IWMI), subsequently provided definitions (Molden 1997; Molden and Sakthivadivel 1999; Molden *et al.* 2003; Molden and Oweis 2007) which were further refined and applied in numerous studies. Agricultural water productivity was usually 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 "economic" terms, such as gross or net value of product. The denominator could be expressed as water supplied or water depleted (such as consumed by crops and/or lost in a sink where it cannot be readily reused). When choosing a particular numerator and denominator, a decision had thus 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 level), the stakeholders, and data availability (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 and thus to articulate recommendations for policy reform and interventions to "close the gap" in the water productivity findings. Substantial differences in spatial and temporal water productivities have been documented, depending on the particular definition of "water productivity" chosen but also with the same definition. For example, among farms in an irrigation district in Iran, water productivity for wheat varied from 0.76 to 0.98 in terms of kg of yield per m^3 of evapotranspiration and from 1.11 to 1.26 in terms of kg of yield per m^3 of transpiration (Vazifedoust *et al.* 2008).[11] Most authors use such findings to argue that a large scope exists to

[11] In response to such findings, some authors recommended to carry out further analyses to increase the sample size, for example, regarding the number of irrigation schemes (Sakthivadivel *et al.* 1999). It was also recommended that water productivity ratios 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 with regard to 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 at least information on these aspects should be provided together with the findings on the ratios (Bessembinder *et al.* 2005).

improve water productivity and thus to increase yields and/or save water. The identified policy implications tend to be wide-reaching, and often not supported with robust evidence from the analyses carried out. Examples are presented below. In an early critique, Barker *et al.* (2003) 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. For instance, an improved management practice may increase water productivity but may also require more labor and other inputs, and therefore might not be cost-effective from a farmer's point of view.

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 examined the effect of subsurface drip irrigation emitter spacing on water productivity (defined as ratio of corn grain yield with 15.5% wet-basis moisture content relative to total crop water consumed) in Kansas, and find no significant impact.

Based on a literature review of 84 publications with data from field experiments, Zwart and Bastiaanssen (2004, p. 115) compared measured water productivity values (defined as ratio of marketable crop yield relative to 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% less water resources". Without further analysis, they identify three factors that influence the soil–plant–water relationship as key for explaining the large variations: 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, p. 101) 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 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".

Other recent studies have 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 agricultural water productivity in a district in India using different definitions. The authors find 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. More resource-intensive modeling allowed them to also assess the effects of alternative management scenarios on the ratio of yield over evapotranspiration for the key crops. Better crop management, for example, was found to increase the ratio.

Some studies modeled crop water productivities on a global scale. Liu *et al.* (2007, p. 478) integrated GIS into the environmental policy integrated climate (EPIC) crop growth model in order to model wheat, 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 ($>1.2\,\text{kg m}^{-3}$), whereas low values ($<0.4\,\text{kg m}^{-3}$) prevailed in most African countries. According to the authors, the differences "suggest that global water use could be reduced through food trade".

Zwart *et al.* (2010a,b, p. 1625) also focused on wheat and, based on input data sets derived from remote sensing, developed a model for mapping water productivity (WATPRO) in terms of estimated yield over evapotranspiration. In an application of the model on a global scale, they find large variations in water productivities, with an average estimate for the 10 major wheat producing countries of $0.93\,\text{kg m}^{-3}$. According to the authors, the model results "facilitate the planning of food production in relation to limited water resources for agriculture".

A few studies with SFP estimates analyzed the effect of other factors on the findings in a more rigorous manner. For example, Belloumi and Matoussi (2006) estimated yield functions for dates in different oasis farms in Tunisia as a function of irrigation water and a number of other explanatory variables — thus assessing the partial effect of irrigation water on variations in date yields while controlling for the effect of other inputs. They applied a Cobb–Douglas function to cross-section data on date yields, and a linear function to related values for water productivity (in terms of water applied). They found water salinity to be a key factor that contributes to both yield and water productivity differences. Alauddin and Sharma (2013) used panel data to explore inter-district differences in water productivity (in terms of consumptive use) for rice in Bangladesh. They applied factor analysis to explore the key variables affecting water productivity, and identified agricultural intensification and technological diffusion as key factors. Granger causality tests suggested that technological diffusion (mainly in terms of high-yielding rice varieties) was a causal factor of water productivity in the majority of districts in Bangladesh.

3.2. *Multi-factor approaches: TFP indices and frontier models*

The productivity and efficiency-related literature in agricultural production economics mostly relies on multi-factor approaches, in particular TFP indices and frontier models. TFP indices have been employed in a large number of empirical studies, mostly at the national level but more recently also at sub-national 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 non-marketed goods and services has long been recognized as a problem (Antle and Capalbo 1988; Gollop and Swinand 1998).[12] Data limitations continue to be a factor (Alston and Pardey 2014), with some authors noting that the contribution of water as a separate input in TFP growth estimates could not be accounted for because of a lack of appropriate data (see for example, Wang *et al.* 2013).

Approaches allowing the partial inclusion of water aspects are shown in studies on agricultural productivity patterns at the country, regional and global levels use included in two recent books by Alston *et al.* (2010a) and Fuglie *et al.* (2012a). For example, Fuglie (2010a) distinguished between irrigated and non-irrigated cropland in a study on agricultural growth in Indonesia. 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, adding 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. Zhao *et al.* (2012) examined Australia's broadacre agriculture[13] and pointed out variable climatic conditions, such as the amount of moisture retained in the soil, as important reason for the significant fluctuations in annual TFP indices. These examples illustrate the challenges of including water aspects in studies at national or higher levels, with attempts being made to approximate irrigation water through the area of land irrigated, and price or opportunity cost of water through irrigation water fees. But these studies do not provide any conclusions related to the effect of water on agricultural productivity patterns.

Water aspects are incorporated in more detail in a few studies of TFP measurement at the sub-national level, such as the provincial and district levels. For

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[12]From a different perspective, Fuglie *et al.* (2012b) also point out that future gains in agricultural need to save not only land but also a wider array of natural resources, such as water, to avoid negative impacts to the environment from agricultural intensification.

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

example, Murgai (1999) provided district-level TFP estimates for the Green and post-Green Revolution period in India's Punjab. By distinguishing between availability of canal irrigation and investment in private tubewells (the former represented as cost associated with the canal-irrigated area, and the latter as an item in the index of capital accumulation), the author was able to identify the type of water source as an additional explanatory factor for the sharp differences in productivity growth across districts and cropping systems. Conradie *et al.* (2009) focused on agricultural TFP in 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, another multi-factor approach frequently used in the agricultural production economics literature are frontier models. Farrell (1957) introduced the original frontier model in a seminal paper that laid 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 conditions by adjusting input use such that for each pair of inputs, the ratio of their marginal products equals the ratio of the input prices). Over the past few decades, frontier models have been widely used in the agricultural economics literature, and 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 the frontier models with a focus on farm-level studies published in the period from 1979 to 2005. Water aspects were not considered. In a review of the 167 articles included in the meta-analysis, we found 28 studies that incorporated water. Most of them included water as one of numerous inputs, or grouped it with other miscellaneous factors in a combined input, and did not further analyze its role in technical efficiency. 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 irrigated dairy farms in Australia, with irrigation water applied as one of the inputs into milk production. They aimed to demonstrate that

DEA was a useful tool for benchmarking and superior to the usual SFP measures, not least because it allowed the identification of influencing factors and best-practice management that could inform the design of extension programs. Their 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. Sarker and De (2004) examined the 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), and found that the efficiency level between the two types of villages did not differ much. They 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 model studies, Ekanayake and Jayasuriya (1987) distinguished between rice farms at the head and tail end 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 end. Comparing estimates from deterministic and stochastic frontier models, the authors find that farmers at the tail end showed a high level of inefficiency in both models, while 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. Ali and Flinn (1989) started out by noting 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 caused profit losses, and recommend the establishment of workshops in the rural areas to help reduce down time due to pump breakdown. Sherlund *et al.* (2002) were concerned about the influence of omitted variables, such as environmental production conditions, on the measurement of technical efficiency. They used panel data for smallholder rice plots under rainfed conditions in Côte d'Ivoire, and applied two specifications for the model: one with and one without environmental variables (including total rainfall and number of rainy days). 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.

DEA and stochastic frontier modeling were applied by Wadud and White (2000) to estimate technical efficiency for rice farmers in Bangladesh. Inefficiency estimates of both methods were similar. When further analyzing inefficiency effects as a function of farm-specific socio-economic factors, environmental factors, and irrigation infrastructure (i.e., diesel-operated irrigation schemes), the authors find that they are positively influenced by irrigation infrastructure. Electrification in rural areas would help further reduce inefficiency.

Besides reviewing the studies included in the meta-analysis, we searched for more recent applications of frontier models. Three studies explicitly incorporated water aspects. 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. They applied a time-varying stochastic frontier model to examine technical efficiency within the context of technical change (i.e., irrigation development), with a dummy variable indicating 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. Yet efficiency was lowered by factors such as the distance to an irrigation canal and the level of siltation in the canals. The management of irrigation water thus appears to play a crucial role in influencing technical efficiency. Gedara *et al.* (2012) investigated the factors affecting technical efficiency of rice farms relying on village reservoir irrigation systems in a district in Sri Lanka. Variation in individual water use was captured by including irrigating time (i.e., the time the water flowed over the land in minutes), and 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% with current technologies and without increasing other inputs. Efficiency improvements could be achieved by encouraging membership in farmer organizations and improved collective actions. Gebregziabher *et al.* (2012) compared the technical efficiency of irrigated and rainfed smallholder plots in Tigray, Ethiopia. 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 similar in characteristics to irrigated plots. They identify a large potential for improving technical efficiency in irrigated agriculture (for example, by training farmers in irrigation agronomy and on-farm water management), while rainfed agriculture seemed to produce close to its production frontier. In the latter case, improving soil moisture would be a measure for shifting the production frontier upward.

We also found two earlier studies, by McGuckin *et al.* (1992) and Karagiannis *et al.* (2003), which applied stochastic frontier modeling to irrigated farms. These studies are of particular interest for our purposes 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.[14] They emphasize that irrigation efficiency is only one dimension of input use, a physical measure of the irrigation technology assuming a level of management, while technical and allocative efficiency are measures of management capability.[15] Both studies include irrigation water (in terms of water applied) as a continuous variable, 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 are not explicitly considered.

McGuckin *et al.* (1992) used farm observations for US corn producers in a homogeneous crop region of Nebraska who applied groundwater by gravity or sprinkler systems as supplemental irrigation. The production 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). Thus, information on field conditions from moisture sensors could be an important factor for improving technical efficiency of irrigation practices.

Karagiannis *et al.* (2003) measured irrigation water efficiency on farms with out-of-season (greenhouse) vegetable cultivation in Crete, Greece. They define irrigation water efficiency not along the lines of the engineering-oriented concept of irrigation efficiency, but 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

[14]Karagiannis *et al.* (2003) refer to McGuckin *et al.* (1992) as well as to Farrell (1957).

[15]As McGuckin *et al.* (1992, pp. 306–307) 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."

inputs used" (p. 58). They note that 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. Thus "relatively inefficient water use in a physical sense can be relatively efficient in a cost sense, and vice versa" (p. 60).[16] While the measures of output-oriented and input-oriented technical efficiencies 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. Modern greenhouse technologies, education, and extension are the main factors associated positively with the degree of water-specific technical efficiency.

3.3. *Deductive methods*

Like TFP indices and frontier models, deductive methods belong to the category of multi-factor approaches. They form a fourth group of methods that is frequently used in the agricultural and irrigation water economics literature for evaluating policies on water use in agricultural production. In contrast to parametric methods, which employ inductive logic (such as econometric procedures) to infer generalizations from individual observations, the approach of the deductive methods involves reasoning from general premises to particular conclusions.[17] Deductive methods range from residual imputation methods for single-product cases to multi-product and multiple-technology cases, and include mathematical programming methods, hydroeconomic models, and CGE models (Young, 2005). They involve the construction of models comprising a set of behavioral postulates (such as profit maximization) and data that typically include assumptions about technology of production and the relevant prices. The data may be provided by empirical studies of production processes, published government reports, and expert opinions. Large-scale programming models, particularly at scales such as the basin level, often include water demand functions for different uses that may be generated by

[16] A similar point was made by Barker *et al.* (2003) in their critique of SFP measures.

[17] As pointed out by Young (2005), it may be more accurate to describe this group of methods as "mostly deductive" versus the "mostly inductive" methods. Deductive methods typically require some inductive steps to arrive at the initial empirical premises, as inductive methods usually involve some deductive reasoning.

various approaches, both deductive and inductive.[18] Deductive methods are flexible with regard the incorporation of different water measures and different scales (i.e., from field, farm and irrigation system to the basin and national levels), including in combination with other methods.

In its basic form, the residual imputation method for a single-product case can be derived from the neoclassical theory of the firm. In general terms, if the production function and the quantities of all other inputs are known, and accurate prices can be assigned to all inputs but one (in this case, water), invoking the production exhaustion theorem allows the imputation of the remainder of total value of product to that input. This allows to derive a point estimate of the producer's net income attributable to the optimally applied input water (Young, 2005). This approach provides the building block for more complex approaches that incorporate changes in water supply and multi-product cases. Foremost are mathematical programming models that can represent the optimum allocation of water and other resources so as to maximize net income, subject to constraints on resource availability or to institutional arrangements. They are advantageous when a wide range of alternative productive technologies (formulated as alternative activities) is to be studied, including alternative levels of inputs to produce a given output, and/or alternative products. Solutions of a mathematical programming model for a range of water supply constraints trace out a set of net total income points, from which a set of value marginal water productivity points can be derived.

Residual imputation methods have been applied extensively since the 1960s (Scheierling 1995). An early application was the linear programming model of Hartman and Whittlesey (1961) to study the adjustments of three "typical farms" in Western Colorado to changes in water supply. They find that besides factors such as input and output prices, the kind of adjustments farmers can make determines the value marginal productivity of water. Moore and Hedges (1963) formulated linear programming models for farms of different sizes in California's San Joaquin Valley with 54 production activities representing combinations of alternative crops, irrigation treatments, and soil grades to estimate the demand for irrigation water and its elasticity. Yaron (1967) performed linear programming studies for kibbutz and household farms in two regions in Israel, and finds that the incorporation of

[18]For example, statistical approaches to estimate price elasticities of water demand can be combined with estimates of water use under particular conditions (e.g., price and level of use) to generate demand functions. Alternatively, smaller scale programming models can themselves be used to generate net benefit estimates as a function of water use. Simple curve fitting with an assumed functional form then leads to the net benefit function (or demand function) which can directly be used in the large-scale programming models.

flexible crop irrigation practices significantly raises estimates for value marginal water productivity. In a study based on a linear programming model of 3,220 equations, Heady *et al.* (1973) dealt with the optimum allocation of water and land resources in 51 water supply regions and 27 market regions of the United States. In a framework of interregional competition and comparative advantage, they examined the effect of alternative water prices, population levels, farming technology, and agricultural policies.

The early linear programming studies typically used constant output prices. This may be problematic, particularly during periods of acute water stress or potential output disruptions. Allowing crop prices to depend on output can be accommodated, as demonstrated in the quadratic programming model used by Howitt *et al.* (1980) to estimate agricultural production and short-run irrigation water use in 14 regions of California.

While the solution of even large linear programming models is relatively straightforward, their calibration often is not (Booker *et al.* 2012). Naïve models rarely result in solutions that reflect observed crop patterns or technology choices under representative water supply and output price conditions. This is typically ascribed to a myriad of producer constraints and hidden costs which may not be evident to the modeler. Calibration is then often carried out using complex sets of linear inequality constraints, which may lead to rigidities in terms of the models' ability to respond to policy scenarios. To circumvent this problem, an approach originally proposed and implemented by Howitt (1995), called positive mathematical programming, recognizes the existence of unobserved heterogeneities and incorporates these into a self-calibration procedure. An example of this increasingly common technique is the study by Medellín-Azuara *et al.* (2009).

Deductive methods can be used to incorporate physical externalities, such as those illustrated in Fig. 3. Approaches that explicitly consider empirical hydrologic structures are called hydroeconomic models (Harou *et al.* 2009; Booker *et al.* 2012). Such integrated models are particularly useful for assessing the effects of improved irrigation efficiency through more capital-intensive on-farm irrigation technology. That water withdrawals and applications are likely to decline, while consumptive use and hence basin-wide water depletion may remain the same or even increase, was demonstrated in theory by Huffaker and Whittlesey (2003) and with integrated modeling by Scheierling *et al.* (2006) and Ward and Pulido-Velasquez (2008). More generally, hydroeconomic models seek to incorporate the notion that water users are potentially linked through complex physical processes, including those between surface and ground water. An early application of such an approach was by Bredehoeft and Young (1970) who explored intertemporal allocation options for improved irrigation outcomes in a linked stream-aquifer system where farmers could draw from both ground and surface water. The explicit treatment of return flows as a physical externality was recently addressed by Taylor *et al.* (2014).

While hydroeconomic models may include important physical linkages, they are mostly partial equilibrium models from an economic perspective, with linkages with key related economic sectors (e.g., labor markets) likely to be absent. General equilibrium approaches are needed to include feedback from farm-level changes to the wider economy, and vice versa. Roe *et al.* (2005) provide a discussion of related issues, and an application of a CGE model to irrigation water management. A CGE application involving conjunctive ground and surface water use is in (Diao *et al.*, 2008). In moving toward CGE models, however, many of the key physical linkages and distinctions between, for example, water application and consumptive use are often lost, and some of the data limitations which challenge TFP studies may reemerge.

4. 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, capturing different aspects of water use and employing a range of methods, with each one having certain limitations that may make them problematic for informing resource allocation and policy.

The irrigation literature, on the one hand, is dominated by studies using SFP measures. They allow the incorporation of different measures of water use (including 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 SFP 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 economics literature on agricultural productivity and efficiency, on the other hand, has relied on inductive methods, mostly TFP indices and frontier models. As multi-factor approaches, these methods avoid some of the key problems of SFP 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 sub-national 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 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 a role 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. 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 of the agricultural productivity and efficiency literature indicates that studies employing inductive methods either incorporate field- and basin-level aspects but focus only on a single input (water), or they apply a multifactor approach but do not tackle basin-level issues. Based on our 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 — provide the flexibility to address some of the shortcomings of the inductive methods. They are multi-factor (and multi-output) approaches that can be applied at any scale and, if linked with hydrological modeling, can incorporate basin-level issues. Their strength is their ability to examine allocation and policy issues in a more direct and comprehensive fashion. There may be large potential gains, both conceptually and for informing policy, from a better integration of the different disciplines and literatures that currently do not seem to inform and build upon each other. For example, better use could be made of empirical estimates of productivity and efficiency parameters to improve the specification of deductive models, making both more useful.

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 aims 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. Yet in many countries with intensifying water scarcity, such as the United States and Australia, data on agricultural water withdrawals and applications are now more systematically collected and reported for different scales. Recent advances in remote sensing technologies allow ever more precise and less costly estimates of consumptive use up to the level of individual fields. Furthermore, based on approaches from other fields in productivity and efficiency analysis, there seems to be scope for improving economic analysis on modeling and assessing agricultural water productivity, including with regard to the relationships of SFP measures and TFP, and technical efficiency and TFP, as well as with regard to possible interlinkages between farms due to return flows. Deductive methods could also be more specifically applied with the aim of assessing agricultural water productivity in a multi-input–multi-output framework. 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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