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Enhancing Water Productivity in Irrigated Agriculture in the Face of Water Scarcity

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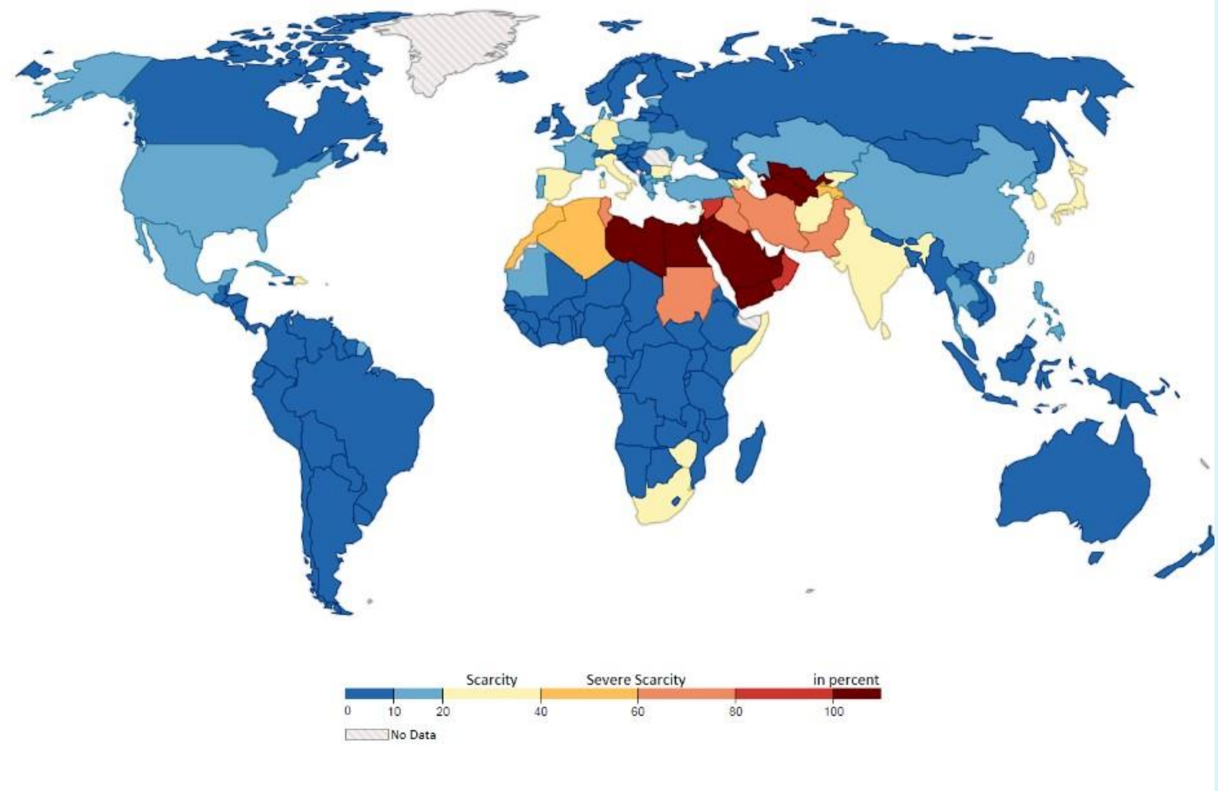
With growing water scarcity in many parts of the world and projections that indicate the need to increase agricultural production and, concurrently, agricultural water use, it is increasingly advocated to focus efforts on enhancing water productivity in irrigated agriculture. Given the large quantities 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. Many international organizations concerned with water management are promoting increase in agricultural water productivity as an important policy goal, and significant public and private investments are being made with this in mind (FAO, 2012; World Bank, 2013; WWAP, 2016). However, most reports and public communications on agricultural water productivity are quite vague. If a definition of the term is given or implied, it is usually along the lines of "more crop-per-drop"—emphasizing water quantity as if it were the only input that mattered—and approaches for enhancing water productivity or efficiency are seldom discussed systematically. The topic is complex due to a number of challenges.

Linking Irrigated Agriculture and Water Scarcity

A first challenge relates to defining water scarcity and showing water used in irrigated agriculture as a contributing factor. This is made difficult by the particular supply and demand characteristics of water, including its mobility, its fluctuating and unpredictable supplies over time and space, and its varying quality. The interdependency among its users is also pervasive. In irrigated agriculture, for example, it is not unusual to find that 50% or more of the water withdrawals from a watercourse are returned, in the form of surface runoff or subsurface drainage, to the hydrologic system (Young, 2005). Only the remainder is "consumed", or lost to the atmosphere, through evaporation from plant and soil surfaces and through transpiration by the plants.

A range of definitions of water scarcity have been proposed and various indicators applied (UNEP, 2012). A widely used indicator is based on a comparison between total water withdrawals and total renewable water resources at the national level. A country is considered to experience "scarcity" if total water withdrawals are between 20% and 40% of total renewable water resources, and "severe scarcity" if this value exceeds 40%. Figure 1 displays this indicator based on the latest available data from the Food and Agriculture Organization (FAO, 2016a). Countries in the Middle East and North Africa (MENA) are all shown to experience severe water scarcity. In other parts of the world, including most countries in South Asia and Central Asia, water is also considered to be scarce or severely scarce. Some countries' water withdrawals are even higher than their total renewable water resources. Saudi Arabia is the most extreme case, withdrawing almost ten times the amount of renewable resources available, and thus relying mostly on non-renewable groundwater.

Figure 1: **Total Water Withdrawals as Percent of Total Renewable Water Resources, 2013 or Latest Year Available**

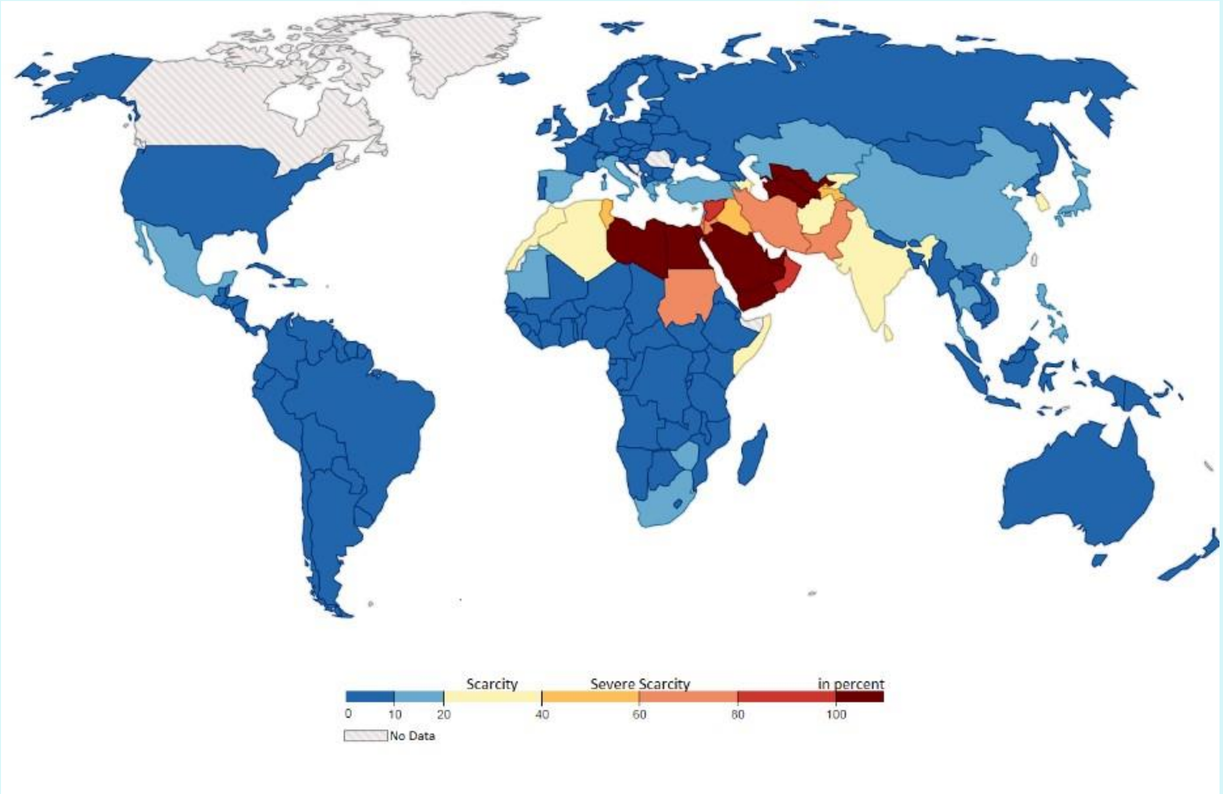


Source: Authors' calculations based on FAO, 2016a.
Notes: Total water withdrawals refer to the annual quantities of water withdrawn for agricultural, industrial and municipal purposes. Total renewable water resources include internal and external water resources (i.e. the annual flow of rivers and recharge of aquifers plus inflows from upstream countries).

In order to illustrate the link between water scarcity and irrigated agriculture, we modify the indicator and, instead of total water withdrawals, include only agricultural water withdrawals in comparison with total renewable water resources. Figure 2 shows the data for the modified indicator. The astonishing result is that the classification of countries with "scarcity" and "severe scarcity" is almost the same as in Figure 1 even though only agricultural withdrawals are considered. This shows the central role of irrigated agriculture in such assessments of water scarcity. In Saudi Arabia, water withdrawn for irrigated agriculture alone is more than eight times the amount of total renewable water resources; in Libya it is about 5 times, in Yemen 1.5 times, and in Egypt slightly more than the amount of total renewable water resources.

Some caveats apply to both indicators. On the one hand, they may underestimate water scarcity. Since they refer to the national level and apply annual water data, they do not indicate water scarcity situations that may occur at the regional or local levels—especially in large countries, such as China—or during the year. They also do not consider water quality issues, or water requirements for the environment. On the other hand, they may overestimate water scarcity since withdrawals include the reuse of return flows that in some instances, especially in the case of irrigated agriculture, can be substantial—such as in Egypt's Nile delta.

Figure 2: **Agricultural Water Withdrawals as Percent of Total Renewable Water Resources, 2013 or Latest Year Available**



Source: Authors' calculations based on FAO, 2016a.
Notes: Agricultural water withdrawals refer to the annual quantities of water withdrawn for irrigation, livestock and aquaculture purposes.

The available data do not allow for an analysis of how changes in agricultural withdrawals have affected water scarcity over time. However, a look at historical data on area equipped for irrigation can provide some insights (FAO, 2016b). Globally, the area equipped for irrigation increased from 164 to 324 million hectares (ha) over the past 50 years. The largest percentage increase occurred in Saudi Arabia (from 0.3 to 1.6 million ha), followed by Libya (from 0.1 to 0.5 million ha) and Yemen (from 0.2 to 0.7 million ha), and these three countries are now experiencing some of the most severe water scarcity. Large increases, in both percentage and absolute terms, also occurred in China (from 45 to 68 million ha) and especially India (from 26 to 67 million ha), a country that is now considered as water scarce.

Agricultural water withdrawals will continue to be a major factor in shaping the water situation worldwide, not least given the expected need for an increase in irrigated area due to continued population growth, rising meat and dairy consumption, and expanding biofuel use (Alexandratos and Bruinsma, 2012). Projections on the likely changes in irrigated area vary, and become more uncertain when the impacts of climate change are taken into account (Elliott et al., 2014). The latter projections suggest that by the end of this century renewable water resources may allow a net increase in irrigated agriculture in some regions—such as in the northern United States, eastern United States and parts of

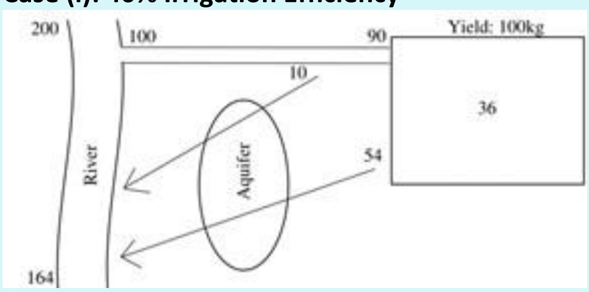
South America and South East Asia—while in other areas the previous expansion would need to be reversed—with a move to rain-fed management in some irrigated regions—such as the western United States, China, MENA, Central Asia, and South Asia.

Defining and Estimating Water Productivity and Efficiency in Irrigated Agriculture

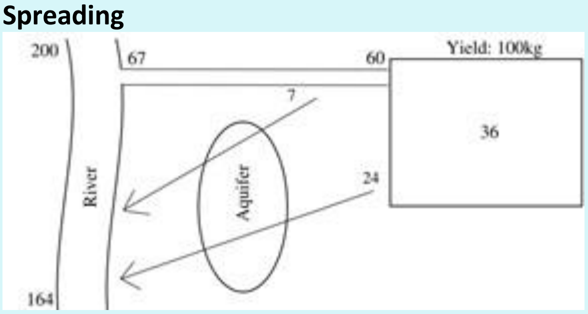
A second challenge relates to the terms agricultural water productivity and efficiency. The various disciplines involved tend to define and estimate the terms in different ways, and to focus on different measures of water. In civil engineering, for example, conveyance efficiency—the ratio of water received at the farm gate relative to the water withdrawn from a water source—is an important term. In irrigation engineering, irrigation efficiency—the ratio of water consumed relative to the water applied on the farm or field—is a classical concept (Jensen, 2007). Agronomists often use the term water use efficiency, and apply different definitions, such as the ratio of yield relative to water consumed (Hsiao et al., 2007). Much of the irrigation literature over the past two decades has addressed water productivity enhancements with crop-per-drop ratios, and strongly influenced the public discussion on agricultural water productivity along these lines (Giordano et al., 2016). The nominator of such ratios can be in physical terms (e.g. kilograms of crop yield) or in so-called "economic" terms (usually yield multiplied by price), and the denominator is expressed in one of the water measures (water withdrawn, applied, or consumed).

Figure 3: **Effects of Changes in Irrigation Efficiency**

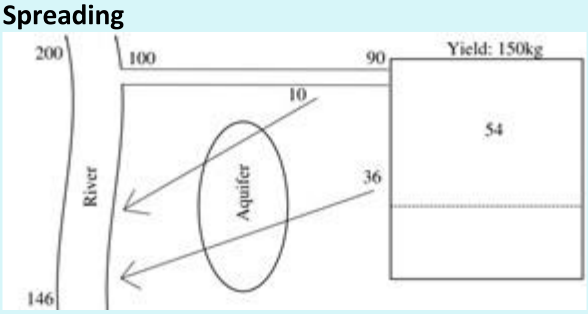
Case (i): 40% Irrigation Efficiency



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



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



Source: Scheierling et al. 2014.

Aside from the formulation, the assumption that an increase in such a ratio (for example, as a result of a switch in irrigation technology) would indicate a desirable change, can be problematic. This is illustrated in Figure 3.

Consider an irrigated area that 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 with a conveyance efficiency of 90%. Seepage from the canal and water not consumed by the crop are assumed to return via a shallow aquifer to the river. In case (i), with an irrigation efficiency of 40%, withdrawal from the river amounts to 100 m^3, water applied is 90 m^3, and consumption 36 m^3. The crop-per-drop ratio (in kilograms per cubic meter) in terms of water withdrawn is then 1.0, in terms of water applied 1.1, and in terms of water consumed 2.8. In case (ii), after the farmer moves to a more capital-intensive irrigation technology (for example, from a gravity system to sprinklers) with an irrigation efficiency of 60%, water application can 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 ratios increase significantly, to 1.5 and 1.8. Yet because consumption and yield does not change, the crop-per-drop ratio in terms of water consumed stays the same at 2.8, as would the river flow downstream of the irrigated area. In case (iii) the farmer, after switching to a higher irrigation efficiency, continues to withdraw the original amount of water and spreads it over an expanded area. Production would increase to 150 kg, and water consumption to 54 m^3. The crop-per-drop ratios for all water measures would stay the same as in case (ii), yet the river flow downstream is reduced from 164 m^3 to 146 m^3. These cases show that the crop-per-drop ratios are influenced by the underlying water measure, and an intervention, such as the introduction of a new irrigation technology, may increase some ratios but not others. A change in a particular ratio may be the result of different causes, and an unchanged ratio may mask significant changes in the underlying water measure as well as in the resulting water availability for downstream uses and/or environmental requirements. These shortfalls of crop-per-drop ratios tend to be neglected in the public discussion.

In economics, including the field of agricultural production economics, productivity and efficiency aspects are defined and analyzed differently than in the irrigation literature. 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 either maximum values of output given inputs, or minimum levels of inputs given output (Fried et al., 2007). A recent survey of the agricultural productivity and efficiency literature that explicitly includes water aspects in productivity and efficiency measurements showed that—while the irrigation literature mostly uses single-factor productivity measures, such as the crop-per-drop ratios—agricultural production economics relies on multi-factor approaches such as total factor productivity (TFP) indices and frontier studies (Scheierling and Treguer, 2016).

Studies based on TFP indices are mostly carried out at the national level. 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. When trying to incorporate water as a separate input, studies applying TFP indices tend to face data problems. Approaches to at least partially account for water aspects include the approximation of irrigation water through the area of land irrigated, and the price or opportunity cost of water through irrigation water fees. For example, in a study of TFP in the global agricultural economy based on FAO data, Fuglie (2010) divides cropland into rainfed cropland and area equipped for irrigation, and includes irrigation fees in the cost share of agricultural land. A limitation of such studies is that they do not provide much insight into the effect of irrigation water on agricultural productivity patterns, or on water scarcity.

Frontier studies, on the other hand, tend to be carried out at the farm level. They measure efficiency relative to a reference “best practice” or efficient frontier, constructed from observed inputs and their output realization. Various statistical techniques are used to calculate the level of inefficiency as the distance to the frontier. Technical efficiency is then an index that ranges between 0% and 100% , and can be interpreted as a proxy measure for managerial effort. It can be studied with an output-orientation (focusing on the ratio of the observed and the maximum levels of output that can be produced with a given level of input and technology) or an input-orientation (focusing on the ratio of the minimum feasible and observed quantity of inputs needed to produce a given level of output and technology). A recent survey of frontier studies incorporating water aspects showed that the majority analyze technical efficiency with an output-oriented approach (Bravo-Ureta et al., 2016). Only a few studies estimate input-oriented technical efficiency, and also analyze the technical efficiency specifically for the input water (focusing on the ratio of the minimum feasible and observed quantity of water applied, given the level of technology and the observed levels of output and all other inputs). Findings for the water-specific technical efficiency suggest that, even without changes in technology, large gains in technical efficiency may be achieved from efforts to improve farmers’ managerial ability related to irrigation water, and water applications could be significantly reduced without affecting yields. However, water quality or return flow issues are not taken into account in these studies.

Clarifying Objectives

A third challenge is that the objective(s) underlying efforts to enhance agricultural water productivity and efficiency are often not clearly spelled out. In much of the irrigation literature, the maximization of agricultural water productivity (usually measured as a crop per drop ratio) seems implicitly assumed to be the overarching objective, and calls are made for efforts to "close the gap" of farmers or whole regions that are below levels achieved elsewhere. In an early critique, Barker et al. (2003) pointed out that while a higher water productivity—in terms of crop per drop—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; this is because enhancements in water productivity may require more labor and other inputs, and therefore might not be cost-effective.

It can be argued that at least three objectives may be pursued with enhancements in agricultural water productivity. The two key objectives are increasing agricultural production, in some cases linked with an attempt to not worsen water scarcity; and conserving agricultural water in response to pressures for reallocating water to other uses (including environmental requirements) or for coping with water scarcity (Scheierling et al., 2014). A third objective that may be linked to the other two objectives is increasing, or at least maintaining, agricultural net revenues.

In the agricultural production economics literature, all three objectives have, to some extent, been reflected. The studies based on TFP indices have focused on increasing agricultural production. Frontier studies have mostly been output-oriented, and thus also more interested in how agricultural production could be raised. A few input-oriented studies use the notion of water-specific technical efficiency to investigate potential water conservation. However, due to their focus on the farm level, they take a perspective that in many cases may be too narrow for deriving broader implications for improving irrigation water management to cope with water scarcity. This is because they seem to only consider water applied, and implicitly assume that any reduction in this measure would constitute water saving. However, this may not be the case in areas where return flows are an important water source for downstream users. Furthermore, given the current institutional arrangements in many locations, farmers may have little incentive to release this water for other uses. This aspect has so far not received much attention, even in studies aimed at conserving water.

Among the frontier studies with estimates of water-specific technical efficiency, a few also evaluate the potential cost savings from adjusting the volume of irrigation water to a technically efficient level while holding all other inputs at observed levels. This is a way to provide some insight into the third objective of increasing agricultural net revenues. A caveat in this case is that the related improvements in managerial efforts may be associated with costs that are not considered in the estimation.

Assessing the Choice of Policy Interventions

Finally, a fourth challenge concerns choosing suitable policy interventions for enhancing agricultural water productivity and efficiency. The understanding of these terms and the related estimation methods often determine the recommendations. In the past, definitions from civil and irrigation engineering have dominated the irrigation literature and the public discussion—as well as the applied interventions, with a focus on investments for improved infrastructure and irrigation technologies. The implicit assumption has been that these investments would contribute to both increased agricultural production and water conservation—at least in terms of water applied. Furthermore, in both developed and developing countries such investments are often subsidized so that they also contribute to the third objective, increasing agricultural net revenues.

The estimation methods also influence the policy recommendations (Scheierling et al., 2014). On the one hand, studies in the irrigation literature that estimate crop per drop ratios for particular crops in terms of yield to water consumed—often employing agro-hydrological models in combination with remote sensing—tend to recommend better soil, water, and crop management to increase the ratios. Frontier studies, on the other hand, tend to emphasize the large potential of moving farms towards the production frontier by improving farmers' managerial skills, and recommend training programs on the use of irrigation technologies and the management of irrigation water.

It seems that more attention should be given to the underlying objectives of efforts to enhance agricultural water productivity. In many parts of the world, especially in the semi-arid and arid regions where water scarcity is already severe and the exploitation of nonrenewable groundwater at unsustainable levels, the conservation of agricultural water is likely to become a main objective. This will require to keep in mind the particular context in which the interventions are to take place. An important aspect is whether return flows matter for downstream uses. Broadly speaking, if they do not matter—due to a lack of downstream uses, or highly saline aquifers that prevent reuse—and water application amounts are fixed, interventions may focus on optimizing the share of applied water for crops' transpiration needs. The adoption of more capital intensive irrigation technologies and strengthened farmers' management skills would move production closer to the so-called frontier. If institutional arrangements permit, the "saved" water could then be transferred to other uses. However, if return flows do matter (that is, if conveyance and on-farm "losses" can be reused, as in Figure 3) and especially if environmental flows and/or water rights of downstream users depend on them—as is the case in some western states of the United States—then interventions may need to focus on reducing water consumed. Only this reduction could be considered "saved" water that is available for reallocation without affecting downstream uses. Suitable interventions would either decrease evaporation (for example, by applying mulching techniques or conservation tillage) or transpiration (for example, by switching to varieties with shorter growing season length). Subsidies for more capital-intensive irrigation technologies in such a context often would not reduce water consumption and may even increase it, especially if water spreading occurs (Scheierling et al., 2006). Also an increase in volumetric charges for irrigation water may not make much additional water available but significantly affect agricultural net revenues. Since it is usually the amount of water applied—and not consumed—that is charged, farmers have an incentive to make adjustments for reducing the former and keeping the latter as much as possible at the same level (for example, with better irrigation scheduling). Substantial amounts of additional water can then only be made available by changes to low consumptive use crops or to non-irrigated agriculture (Scheierling et al., 2004).

Going Forward

In many regions with growing water scarcity and unsustainable water use, coupled with the influence of climate change, it may be not be possible that water application amounts in agriculture can remain fixed, as assumed above. In such cases, the institutional arrangements governing water reallocations will become a central feature of water policy, and reform efforts need to focus on limiting the negative impacts on agricultural production and farmers as well as on downstream users, including the environment.

There seems to be scope for advancing economic assessments of agricultural water productivity, including all sources of productivity, and providing insights on how water could be used more efficiently and productively in different contexts and with different objectives. This may involve learning from and possibly harmonizing approaches used within economics and other concerned disciplines. Deductive methods—such as hydroeconomic models—that are not much discussed in the agricultural productivity and efficiency literature but constitute an important part in the agricultural and irrigation water economics literature, could also be more specifically applied to assess agricultural water productivity in a multi-input multi-output framework. These methods have the additional advantage that they can be applied from field or farm to basin and national levels, and consider the potential interlinkages among water users with the incorporation of the different water measures. In order to facilitate this progress, more efforts will have to be made to improve the availability of data on irrigation water use.

For More Information

Alexandratos, N., and J. Bruinsma. 2012. *World Agriculture towards 2030/2050*. The 2012 Revision, ESA Working Paper No. 12-03, Rome: Food and Agriculture Organization of the United Nations.

Barker, R., D. Dawe, and A. Inocencio. 2003. “Economics of water productivity in managing water for agriculture.” In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*, eds. J.W. Kijne, R. Barker, and D. Molden, 19-36. Wallingford, UK: CAB International.

Bravo-Ureta, B.E., R. Jara-Rojas, M.A. Lachaud, V.H. Moreira, S.M. Scheierling, and D.O. Treguer. 2016. *Agricultural Productivity and Water: Evidence from the Frontier.* Policy Research Working Paper, World Bank, Washington, D.C. Forthcoming.

Coelli, T.J., D.S.P. Rao, C.J. O’Donnell and G.E. Battese. 2005. *An Introduction to Efficiency and Productivity Analysis.* 2nd ed. Springer, New York, USA.

Elliott, J., D. Deryng, C. Mueller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Floerke, Y. Wada, N. Best, S. Eisner, B.M. Fekete, C. Folberth, I. Foster, S.N. Gosling, I. Haddeland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang, and D. Wisser. 2014. “Constraints and Potentials of Future Irrigation Water Availability on Agricultural Production under Climate Change.” *Proceedings of the National Academy of Sciences (PNAS)* 111(9), 3239-44.

Food and Agriculture Organization of the United Nations (FAO). 2012. *Coping with Water Scarcity: An Action Framework for Agriculture and Food Security.* Water Reports 38, Rome: FAO.

Food and Agriculture Organization of the United Nations (FAO). 2016a. *AQUASTAT Main Database*. Available online: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en

Food and Agriculture Organization of the United Nations (FAO). 2016b. *FAOStat*. Available online: http://faostat3.fao.org/home/E

Fried, H.O., C.A. Knox Lovell, and S.S. Schmidt. 2007. “Efficiency and Productivity.” In *The Measurement of Productive Efficiency and Productivity*, eds. H.O. Fried, C.A. Knox Lovell and S.S. Schmidt, 1-106. New York, NY: Oxford University Press.

Fuglie, K.O. 2010. “Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data.” In *The Shifting Patterns of Agricultural Production and Productivity Worldwide,* eds. J.M. Alston, B.A. Babcock, and P.G. Pardey, 63-95. Ames, Iowa: The Midwest Agribusiness Trade Research and Information Center.

Giordano, M.A., H. Turral, S.M. Scheierling, D.O. Treguer, and P.G. McCornick. 2016. *Beyond 'More Crop per Drop': Evolving Thinking on Agricultural Water Productivity*. International Water Management Institute (IWMI) Research Report, Colombo, Sri Lanka. Forthcoming.

Hsiao, T.C., P. Steduto, and E. Fereres. 2007. "A Systematic and Quantitative Approach to Improve Water Use Efficiency in Agriculture." *Irrigation Science* 25 (3): 209-231.

Jensen, M.E. 2007. "Beyond Irrigation Efficiency." *Irrigation Science* 25 (3): 233-245.

Scheierling, S.M., R. Young, and G.E. Cardon. 2004. "Determining the Price Responsiveness of Demands for Irrigation Water Deliveries vs. Consumptive Use." *Journal of Agricultural and Resource Economics* 29(2): 328-345.

Scheierling, S.M., R.A. Young, and G.E. Cardon. 2006. "Public Subsidies for Water-conserving Irrigation Technologies: Hydrologic, Agronomic and Economic Assessments." *Water Resources Research* 42, W03428.

Scheierling, S.M., D.O. Treguer, J.F. Booker, and E. Decker. 2014. *How to Assess Agricultural Water Productivity? Looking for Water in the Agricultural Productivity and Efficiency Literature*. Policy Research Working Paper 6982, World Bank, Washington, D.C.

Scheierling, S.M., and D.O. Treguer. 2016. "Water Productivity in Agriculture: Looking for Water in the Agricultural Productivity and Efficiency Literature." *Water Economics and Policy* 2(3). DOI: 10.1142/S2382624X16500077.

United Nations Educational, Scientific, and Cultural Organization (UNESCO). 2009. *Water in a Changing World: The United Nations World Water Development Report 3*. Paris: UNESCO Publishing, and London: Earthscan.

United Nations Environment Programme (UNEP). 2012. *Measuring Water Use in a Green Economy.* A Report of the Working Group on Water Efficiency to the International Resource Panel. Nairobi, Kenya.

World Bank. 2013. *Agriculture Action Plan 2013-2015. Implementing Agriculture for Development*. Washington, D.C.: World Bank.

United Nations World Water Assessment Programme (WWAP). 2016. *The United NationsWorld Water Development Report 2016: Water and Jobs.* Paris, UNESCO.

Young, R.A. 2005. *Determining the Economic Value of Water: Concepts and Methods*. Washington, D.C.: Resources for the Future.

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