# CHALLENGES AND POLICIES FOR GLOBAL WATER AND FOOD SECURITY[1]

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## INTRODUCTION

Water is essential to grow food; for household water uses, including drinking, cooking, and sanitation; as a critical input into industry; for tourism and cultural purposes; and in sustaining the earth's ecosystems. But this essential resource is under threat. Increasing scarcities in much of the world pose challenges for national and sub-national governments and for individual water users. The challenges of growing water scarcity are compounded by increasing costs of developing new water; degradation of soils in irrigated areas; over pumping and depletion of groundwater; water pollution and degradation of water-related ecosystems; and wasteful use of already developed supplies, encouraged by subsidies and distorted incentives that influence water use (Rosegrant 2015).

Growing water scarcity and water quality constraints are a major challenge to future outcomes in food security, especially since agriculture is expected to remain the largest user of freshwater resources in all regions of the world for the foreseeable future, despite rapidly growing industrial and domestic demand. As non-agricultural demand for water increases, water will be increasingly transferred from irrigation to other uses in many regions. In addition, the reliability of the agricultural water supply will decline without significant improvements in water

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management policies and investments. The intensifying sectoral competition and water scarcity problems, along with declining reliability of agricultural water supply, will put downward pressure on food supplies and continue to generate concerns for global food security.

Ringler et al. (2016) project future water stress, showing that in 2010, 36 percent of the global population — approximately 2.4 billion people — live in water-scarce regions and 22 percent of the world's gross domestic product (GDP) (US$9.4 trillion at 2000 prices) is produced in water-short areas (Figure 1). Moreover, 39 percent of global grain production is in water-stressed regions. In China and India and many other rapidly-developing countries, water scarcity has already started to materially risk growth — in these two countries alone 1.4 billion people live in areas of high water stress today.

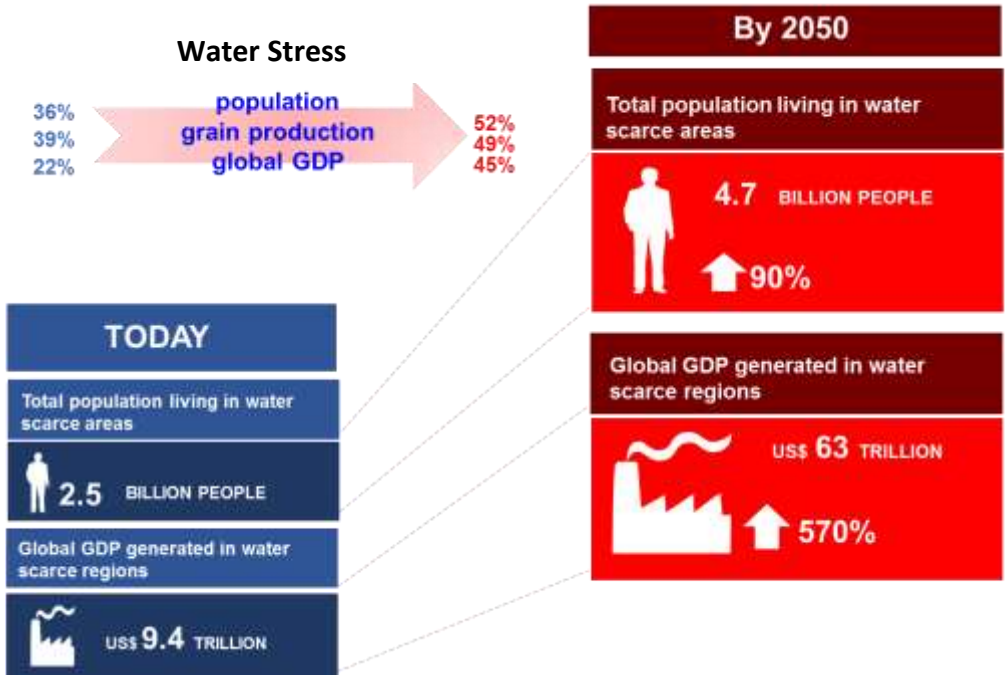


**Figure 1. Projected water stress to 2050 under business-as-usual scenario.**

Source: Author, based on Ringler et al. 2016

Business-as-usual (BAU) levels of water productivity under a medium economic growth scenario will not be sufficient to reduce risks and ensure sustainability. Under BAU, 52 percent of the global population (4.8 billion people), 49 percent of global grain production, and 45 percent (US$63 trillion) of total GDP will be at risk due to water stress by 2050, which will likely impact investment decisions, increase operation costs and affect the competitiveness of certain regions (Figure 1) (Ringler et al. 2016).

In the rest of the paper, I summarize projections for BAU outcomes for food security, showing that, under the BAU scenario, increasing water scarcity and other factors are projected to lead to slowing agricultural growth and rising food prices. Then evidence is provided on the impact of water scarcity on economic growth, and relationship between climate change and water resources is summarized. The next section deals with the policies, management, and technologies, and investments that can lead to a better future for water and food security, and an alternative scenario is examined to see whether plausible increases in water and crop productivity can provide significantly better outcomes for water and food security.

## WATER AND FOOD SECURITY

With declining availability of water and limited land that can be profitably brought under cultivation, expansion in area will contribute very little to future production growth. Slow growth in investment in agricultural research, irrigation, and rural infrastructure in developing countries are likely to dampen productivity growth, and climate change will reduce the rate of growth in productivity. These supply factors, coupled with growing population (mainly in Africa and South Asia) and rising income, are projected to lead to rising food prices and slow improvements in food security under BAU conditions, as shown in Figures 2 and 3.

International prices of cereals are projected to increase by 20 percent even without climate change. With climate change, across a range of general circulation models, the mean price increase between 2010 and 2050 is projected to be approximately 50 percent. Meat prices are projected to increase by 20 percent as well, with a slight decline in prices after 2040 as developed countries, China, and Brazil reduce their per capita meat consumption (Figure 2).

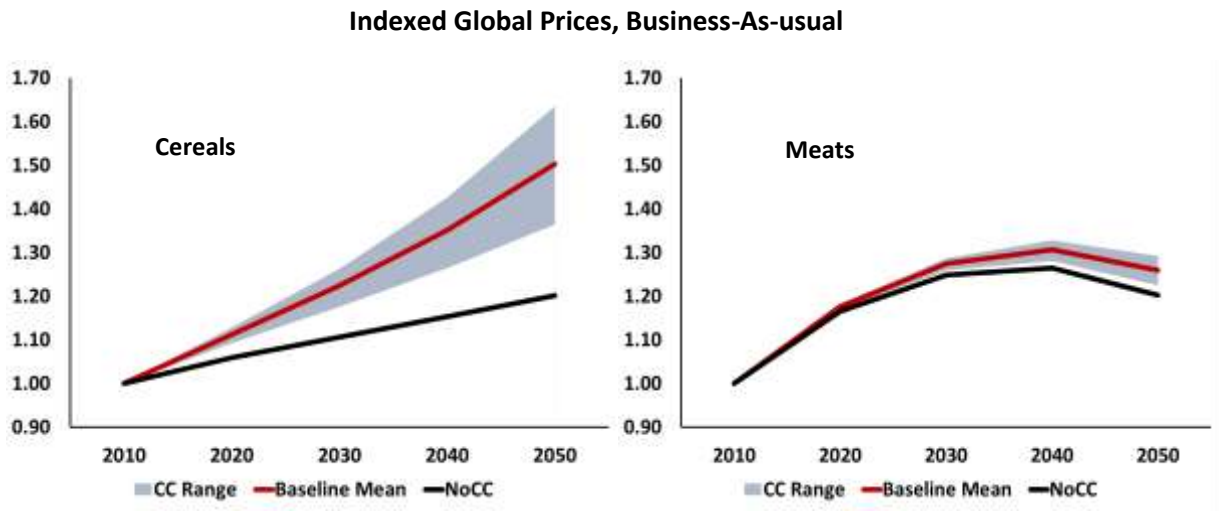


**Figure 2. Projected prices of cereals and meats with and without climate change, business-as-usual, real prices indexed to 2010.**

Source: Author from IMPACT Model results

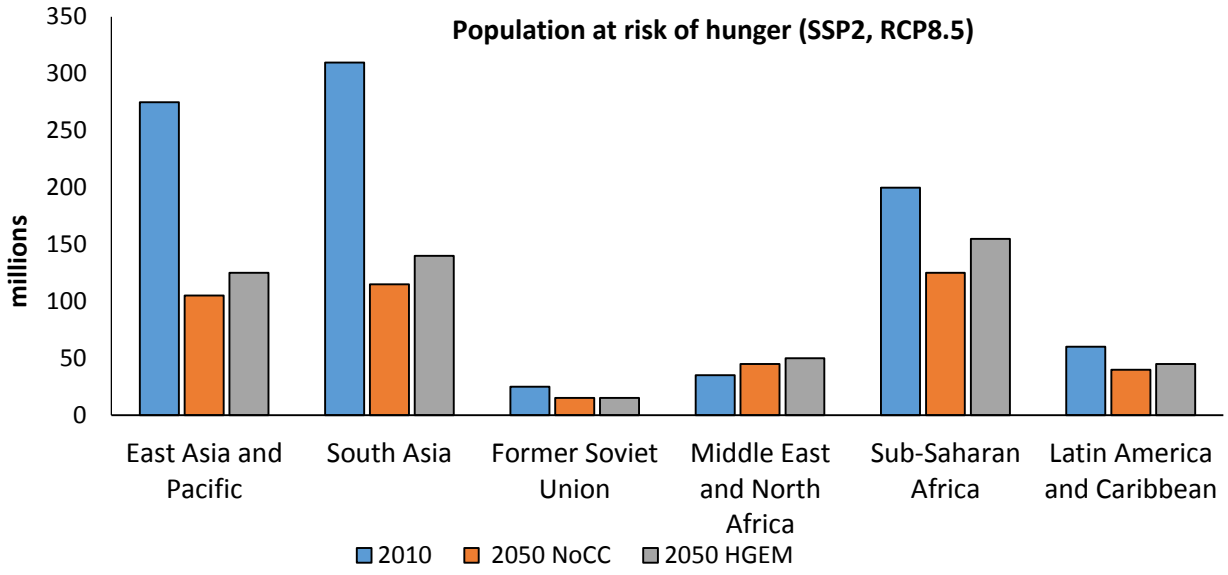


**Figure 3. Projected population at risk of hunger in 2050 with and without climate change, using shared socioeconomic pathways 2 (SSP2) and representative concentration pathway (RCP) 8.5.**

Source: Author from IMPACT Model results

Other food prices increase in the range of 10-30 percent. These higher food prices also lead to slow reductions in hunger. Although Figure 3 shows that there are projected reductions in the population at risk of hunger both with and without climate change, these reductions are far smaller than the targets in the sustainable development goals, which call for ending hunger in 2030. Even by 2050, under climate change it is projected that there will still be 155 million people at risk of hunger in Sub-Saharan Africa, 140 million in South Asia, and 530 million across the developing regions.

## WATER AND ECONOMIC GROWTH

In addition to the impacts on agriculture and food security, water scarcity and water-related investments can increase economic productivity and growth. Sadoff et al. (2015) summarize much of the evidence on this relationship. They conclude that the connection between water security and economic growth is intuitively clear, but that the empirical evidence of this relationship is scarce. More recent econometric analyses have considered variability in precipitation in addition to mean levels. Brown et al. (2011), cited in Sadoff et al. (2015), show that rainfall variability, floods, and droughts have a statistically significant negative detrimental impact on different measures of economic growth in Sub-Saharan Africa. Brown et al. (2013) find that anomalously low or high precipitation has a negative economic effect, thereby providing evidence that variability in precipitation can hinder growth.

Sadoff et al. (2015), using an econometric model, show that runoff has a statistically significant positive relationship with growth that indicates that greater water availability has a significant and positive causal effect on economic growth. Drought was shown to have a statistically significant negative impact on economic growth as well. On average, a major drought (affecting 50 percent or more of a country's area) was found to reduce economic growth (as measured by per capita GDP) by about half a percentage point in that year (e.g., reduced from 3 percent to 2.5 percent per year). Flood extent likewise had a negative impact on per capita GDP growth. Simulations that determined the benefits of reduced drought impacts also demonstrated that the effect of droughts may compound over a long time period. Sadoff et al. (2015) also found that the effects of hydro-climatic variables on growth are strongest in poor countries and countries with high human water stress, high dependence on agriculture, or both.

The World Bank (2016) simulates the impact of water on economic growth using a Computable General Equilibrium (CGE) model, which captures how impacts in the water sector affect the rest of the economy. The economic consequences are highly unequal with the worst effects in the driest regions. The expected global damages are small relative to the expected global GDP in 2050. But the global loss is a highly misleading estimate because significant variations exist between regions. Western Europe and North America, where much global GDP is produced, experience negligible damages in most scenarios. The bulk of losses are in the Middle East, the Sahel, and Central and East Asia, and the magnitude of losses is largely driven by the level of the water deficit. GDP in 2050 under a water-constrained scenario ranged from -7 percent in East Asia, -7 percent in Central Africa, -11 percent in Central Asia, -11 percent in Sahel, and -14 percent in Middle East (World Bank 2016).

But economic feedback effects and adjustments can also limit the damage from water shortfalls. Apart from the direct effect of water shortages on yields and crop areas, macroeconomic outcomes are similarly affected by prices and international trade. Liu et al. (2014), also using a CGE model, find that even countries experiencing negative output shocks due to reduced irrigation availability may gain from higher commodity prices caused by the shocks. Regions can take advantage of trade to adjust the composition of agricultural income and specialize in more beneficial commodities. These adjustment effects, which are mediated by markets, reduce the initial effect of reduced water availability in farming.

## CLIMATE CHANGE IMPACTS ON WATER

Climate change is projected to cause substantial changes in mean annual streamflows, the seasonal distributions of flows, melting of snowpack, and increased probability of extreme high-

or low-flow conditions. Climate change impacts on water resources include changes in the timing of water availability due to changes in glaciers, snow and rainfall; changes in water demands due to increased temperatures; changes in surface water availability and groundwater storage; an increased number and intensity of extreme climatic events (droughts and floods); changes in water quality; and sea-level rise (Rosegrant, Ringler and Zhu 2014). World Bank (2010) shows that most places will experience more intense and variable precipitation, often with longer dry periods in between (Burke and Brown 2008; Burke, Brown, and Christidis 2006). The effects on human activity and natural systems will be widespread.

The ultimate outcome of climate change and its effects on water availability are not known with precision. Unknowns include geographic location, direction of change (less/more precipitation), degree of change in precipitation (low/high), change in precipitation intensity (low/high), and timing (within the next five years or over multiple decades). Shifting precipitation patterns and warming temperatures could increase water scarcity in some regions while other areas may experience increased soil-moisture availability, which could increase opportunities for agricultural production (Malcolm et al. 2012). But as the World Bank (2010) noted, these uncertain changes are certain to make it harder to manage the world's water, with people feeling many of the effects of climate change through water. Climate change will make flexible water allocation more important, to adjust to changes in the timing of water availability, changes in water demands, changes in surface water availability, and extreme events.

## WATER POLICIES AND INVESTMENTS

Meeting these challenges will require action on many fronts. This section summarizes critical priorities to enhance water use efficiency and productivity.

### Investment in crop breeding for yield per unit of water and land

The first key to better water use productivity is not directly part of the water sector: productivity gains for both irrigated and rainfed agriculture. Cai and Rosegrant (2003) found that, while both the increase in crop yield and improvement in basin efficiency contribute to the increase in water productivity (crop yield per meter of applied water), the major contribution comes from increases in the crop yield. Moreover, progress on rainfed crop yield per hectare and per unit of water food security would reduce pressure on irrigated crops. Plant breeding can improve plant biomass/unit of water through transpiration rates and efficiency of biomass growth per unit of transpiration. Although it is a challenging breeding goal, improvement in crop yield per unit of water use continues and has further potential (Richards et al. 1993; Richards et al. 2002; Ortiz et al. 2007). For effective breeding for drought tolerance and other traits to get more yield per unit of water, the availability of diverse genes is essential; to support a broad and targeted gene pool, the tools of biotechnology should be employed, including marker-assisted selection, cell and tissue culture, and gene editing, even if countries elect to forego transgenic breeding (Morison et al. 2008; Christensen and Feldmann 2007).

**Adoption of new irrigation technology and farming systems**

Improved irrigation technology, such as drip and sprinkler irrigation crop and water management and technology, such as enhanced water harvesting, conservation tillage, precision farming that optimizes application of water and other inputs within the field, can be important means to improve yields and enhance rural and farm incomes. However, because of the interconnected nature of water, with runoff from one water user often being available to other users through return flows, different outcomes are possible when a new technology is put in place. For example, new technology can save water that would otherwise evaporate unproductively, providing net system benefits; divert water that would otherwise be used downstream by others, which merely shifts benefits between farmers, rather than generating new benefits; or induce increased water use by increasing the profitability of irrigation for individual farmers rather than saving water (World Bank 2010). Farmers have many reasons to adopt advanced irrigation technology, including increased income from higher value crops, convenience, labor-saving, and lower pumping costs, but real water savings are more difficult to achieve and often limited (Perry et al. 2009). Achieving the potential benefits of new technologies and farming systems is promoted by a water allocation system that recognizes these hydrological realities. Well-specified water rights and allocations have the potential to significantly improve water and food security and tap the potential gains of technology.

**Establishment of water rights and water trading**

Water rights are the cornerstone of efficient and equitable water management. Secure and well-defined water rights provide incentives for investment in more efficient technology; making those water rights tradable provides additional incentives to optimize the economic value of

water. Moreover, a properly managed system of tradable water rights provides incentives for water users to internalize the external costs imposed by their water use, reducing the pressure to degrade resources (Easter and Huang 2014; Rosegrant and Binswanger 1994). Young (2015) lays out a blueprint for establishing water rights and trading, based in significant part on the experience in the Murray Darling River Basin in Australia. The conditions for effective water rights should include a perpetual right to a proportion (share) of all allocations made in the river basin or system, and the actual allocation made in any season should be expressed as a share of the actual allocation based on available water determined in a transparent process and accounting for system evaporative losses and environmental outcomes, including water quality and flows to the sea (Young 2015; Young and McColl 2009).

The establishment of water rights that create incentives for efficient use of water together with trading systems to optimize economic returns has proven very difficult even in developed countries. In developing countries, the high costs of measuring and monitoring water use, where infrastructure and institutions are weak, and irrigation systems are often large and service many small farmers, can also be a major constraint to implementation water rights and trading. Adding to the difficulty of reform, both long-standing practices and cultural and religious beliefs have treated water as a free good, and entrenched interests benefit from the existing system of subsidies and administered allocations of water (Rosegrant, Ringler and Zhu 2009). Effective development of well-defined water rights and trading in developing countries would be enhanced by improvement in irrigation technology for conveyance, diversion, and metering; institutional improvement in management of irrigation systems; and in many cases, development of community organizations to manage water allocation. Development of well-specified water rights and trading is likely to be a medium- to long-term process in most developing countries.

An initial focus on realistic allocation of water on a seasonal basis together with registration of rights based on shares would be a major first step.

Groundwater use in much of the world has increased very rapidly in a very short period of time, particularly in Asia, following the availability of cheap pumps, often combined with subsidized energy and water. While expansion of groundwater use has been highly beneficial, overdrafting is excessive in many instances, causing land subsidence, salinization, and other degradation of land and water quality in the aquifer. The principles of groundwater management through water rights and trading are essentially the same as described above, but even more complex than surface systems, due to the invisibility of the resource, the lack of data on safe yield or availability, and groundwater movement. Elements of successful groundwater management include recognized user rights, monitoring processes, means for sanctioning violations, and procedures for adapting to changing conditions. Again, institutional capabilities to establish such systems are lacking in most developing countries but measuring groundwater and establishing clear rights would be an important step forward.

**Capital investment in irrigation and water**

Because new investments in irrigation and water supply are increasingly expensive and politically sensitive, hard infrastructure investment has a reduced role globally compared with past decades when dam-building and expansion of irrigated area drove rapid increases in irrigated area and crop yields, particularly in developing countries (Rosegrant, Ringler, and Zhu 2009). But substantial potential still exists for irrigation expansion in some regions of the world. The World Bank's Africa Infrastructure Country Diagnostic (AICD) study (You et al. 2011) concluded that Africa has the potential to add at least 16 million hectares of profitable large-scale

irrigation. Xie et al. (2014) showed an even larger potential for profitable smallholder irrigation expansion in Sub-Saharan Africa. Area expansion potential was identified as up to 30 million ha for motor pumps, 24 million ha for treadle pumps, 22 million ha for small reservoirs and 20 million ha for communal river diversions. The technologies can benefit between 113 and 369 million rural people in the region generating net revenues of US $14–22 billions depending on technology.

Finally, large additional investments in water treatment and sewage disposal plants will be required. Various estimates exist for the necessary investments to improve sanitation standards, especially in the developing world. In a study commissioned by the World Health Organization, Hutton and Haller (2004) estimate that access for all to improved water and sanitation services would cost around US$22.6 billion per year and access for all to regulated in-house piped water supply with quality monitoring and in-house sewerage connection with partial treatment of sewage would require a total investment of US$136.5 billion per year.

## IMPACTS OF IMPROVED WATER USE EFFICIENCY AND PRODUCTIVITY

Can plausible implementation of the measures described above significantly improve water and food security compared to the outcomes in the BAU scenario described above? Rosegrant et al. (2013) simulate an alternative scenario for water and food security that combines water use efficiencies in the domestic, industrial and irrigation sectors to reflect direct water-saving effects, together with higher crop productivity growth per unit of water consumed, and the resultant higher GDP growth stimulated by higher agricultural productivity. We utilize the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model: a partial equilibrium, multi–commodity, multi-country model which generates projections of global food

supply, demand, trade, and prices and water supply and demand (see Rosegrant et al. 2012 for a detailed description of IMPACT). The CGE model GTEM (Ahammad and Mi, 2005) was used iteratively with the IMPACT model to generate the multiplier effects from agricultural and water sector productivity growth to GDP growth. The efficiency gains for industrial and residential water use are taken from the WaterGAP model (Ozkaynak et al. 2012). The underlying drivers for water use efficiency gains as described in Global Environment Outlook V (GEO5) report include stringent efficiency measures are taken in industry and residential water use and climate policies lead to a reduced demand for thermal cooling in power generation as fossil-fuel-powered plants are partly replaced by renewable energy sources. For agriculture, we estimate the basin water use efficiency gains based on more efficient transpiration (including drought resistant varieties and other advances in research as described above), reduced non-beneficial evapotranspiration (ET) and reduced losses to water sinks (e.g. due to water-conserving irrigation and crop management technologies and reduced evaporative losses during conveyance). The average global basin-level water use efficiency gains are 8.8 percent by 2030 and 14.5 percent in 2050 compared to the BAU scenario (Rosegrant et al. 2013).

The simulated improvements in efficiency result in an improvement in irrigation water supply reliability (IWSR), which is defined as the annual ratio of irrigation water supply to demand. The degree of improvement varies by country and regions, but globally, IWSR is 0.619 under the BAU scenario and 0.726 under the higher efficiency and productivity scenario. This improvement results in higher reliability than in the 2000 base year, while accommodating significant increases in irrigated area (Rosegrant et al. 2013).

With higher crop yield growth and larger crop production under the more efficient scenario, prices for most crops, including rice, wheat and maize, and oils decline relative to the BAU scenario despite the higher income growth generated under the more productive scenario. Price declines are generally in the range of 10-20 percent in 2050 compared to the baseline. Prices for meat, fruits, and vegetable increase slightly, with the effects beef, lamb, and poultry increase, reflecting the impact of higher income on these commodity markets. Per capita food demand increases as a result of higher income growth and lower agricultural commodity prices.

Rosegrant et al. (2013) also project the number of people facing the risk of hunger in the different regions of the world. With higher water and productivity growth expanding the food supply and pushes down food prices and improve GDP growth to boost per capita food consumption there will be fewer people at the risk of hunger. In the projected alternative scenario, the number people at the risk of hunger declines significantly for all developing regions. The two regions that have the most severe hunger issues gain the most. Sub-Saharan Africa has the biggest percentage drop in hunger, with a 44 percent reduction in the population facing the risk of hunger in 2050 compared to BAU, reducing the number of hungry by 66 million in 2050 relative to BAU.

## CONCLUSIONS

Water scarcity will be increasing in much of the world, and together with climate change and other factors will cause relatively slow growth in agricultural productivity and slow progress in reduction of hunger. But a plausible scenario for water and crop productivity growth—predicated on a set of water allocation reforms, new water technologies and farming systems, investment in crop research to increase yield with respect to water, and selective new investment

in irrigation and water sanitation and sewage, can significantly improve the water and food security outcomes. Finally, the precise mix of water policy and management reform and investments, and the feasible institutional arrangements and policy instruments to be utilized must be tailored to specific countries and basins, and will vary across underlying conditions and regions, including levels of development, agroclimatic conditions, relative water scarcity, level of agricultural intensification, and degree of competition for water. These solutions are not easy, and they take time, political commitment, and money.

## LITERATURE CITED


Ahammad, H. and R. Mi. 2005. Land use change modeling in GTEM: Accounting for forest sinks. Australian Bureau of Agricultural and Resource Economics (ABARE) Conference Paper 05.13, presented at the workshop, Energy Modeling Forum 22: Climate Change Control Scenarios, 25-27 May. 2005. Stanford University, Palo Alto, CA.

Brown, C., R. Meeks, K. Hunu, and W. Yu. 2011. Hydroclimate risk to economic growth in sub-Saharan Africa. *Climatic Change* 106: 621-647.

Brown, C., R. Meeks, Y. Ghile, and K. Hunu. 2013. Is water security necessary? An empirical analysis of the effects of climate hazards on national-level economic growth. *Philosophical Transactions of the Royal Society* A, 373(2036), 2012.0416.

Burke, E. J. and S. J. Brown. 2008. Evaluating Uncertainties in the Projection of Future Drought. *Journal of Hydrometeorology* 9 (2): 292–99.

Burke, E. J., S. J. Brown, and N. Christidis. 2006. Modeling the Recent Evolution of Global Drought and Projections for the 21st Century with the Hadley Centre Climate Model. *Journal of Hydrometeorology* 7: 1113–25.

Cai, X. and M.W. Rosegrant. 2003. *Water productivity and food security, current situation and future options*. *In* J.W. Kijne (ed) Water Productivity In Agriculture: Limits and Opportunities for Improvement. Wallingford, UK: CABI.

Christensen, C. and Feldmann, K. (2007) 'Biotechnology Approaches to Engineering Drought Tolerant Crops', in M. Jenks, P. Hasegawa, and S. Jain (eds) Advances in Molecular Breeding Toward Drought and Salt Tolerant Crops, Springer, Dordrecht, The Netherlands. pp 333-357.

Easter, K.W. and Q. Huang (eds.), Water Markets for the 21st Century: What Have We Learned? Global Issues in Water Policy 11:35-65. Heidelberg, New York, London: Springer.

Hutton, G. and L. Haller. 2004. Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level. Water, Sanitation and Health Protection of the Human Environment. World Health Organization. Geneva, Switzerland. http://www.who.int/water_sanitation_health/wsh0404.pdf

Liu, J., T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler. 2014. International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change* 29: 22–31 http://www.sciencedirect.com/science/article/pii/S095937801400137X

Malcolm, S., E. Marshall, M. Aillery, P. Heisey, M. Livingston, and K. Day-Rubenstein. 2012. Agricultural Adaptation to a Changing Climate: Economic and Environmental Implications Vary by U.S. Region. Economic Research Report No. (ERR-136) 84 pp, July 2012. http://www.ers.usda.gov/media/848748/err136.pdf

Morison, J. et al. 2008. Improving Water Use in Crop Production. *Philosophical Transactions of the Royal Society* 363: 639-658. http://rstb.royalsocietypublishing.org/content/363/1491/639.full.pdf+html.

Ortiz, R. M. Iwanaga, M. Reynolds, H. Wu, and J. Crouch. 2007. "Overview on Crop Genetic Engineering for Drought-Prone Environments." Journal of SAT Agricultural Research. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) http://www.icrisat.org/journal/SpecialProject/sp3.pdf.

Ozkaynak, B., L. Pinter, D.P. van Vuuren, L. Bizikova, V. Christensen, M. Floerke, M. Kok, P. Lucas, D. Mangalagiu, R. Alkemade, T. Patterson, J. Shilling, D. Swanson, A. Bassi, F. Feldmann, J. Jäger, W. Ochola, W. Qu, K. Ramakrishna, C. Ringler, P. Ertor, N. Pervushina,

M. Billot, and N. Sharma. 2012. Scenarios and sustainability transformation. In Global Environment Outlook 5 (GEO 5). Environment for the future we want, ed. Matthew Billot, Ludgarde Coppens, Volodymyr Demkine, Salif Diop, Peter Gilruth, Jason Jabbour, Josephine Nyokabi Mwangi, Fatoumata Keita-Ouane, Brigitte Ohanga, and Nalini Sharma. Malta: United Nations Environment Programme (UNEP). Chapter 16. Pp. 419-456. http://www.unep.org/geo/pdfs/geo5/GEO5_report_C16.pdf

Perry, C. P. Steduto, R.G. Allen, and C.M. Burt. 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management* 96: 1517–1524

Richards, C. Lopez-Castaneda, H. Gomez-Macpherson, A. Condon. 1993. Improving the efficiency of water use by plant breeding and molecular biology. *Irrigation Science* 14: 93-104.

Richards, R. G. Rebetzke, A. Condon, and A. van Herwaarden. 2002. Breeding Opportunities for Increasing the Efficiency of Water Use and Crop Yield in Temperate Cereals. *Crop Science* 42: 111-121.

Ringler, C., T. Zhu, S. Gruber, R. Treguer, A. Laurent, L. Addams, N. Cenacchi and T. Sulser. 2016. Role of water security for agricultural and economic development – concepts and global scenarios. In Handbook on water security, ed. Claudia Pahl-Wostl, Anik Bhaduri, and Joyeeta Gupta. Chapter 11. Pp. 183-200. Cheltenham, UK: Edward Elgar Publishing Limited.

Rosegrant, M W. 2015. Global outlook for water scarcity, food security, and hydropower. In Handbook of water economics and institutions, ed. Kimberly Burnett, Richard Howitt, James A. Roumasset, and Christopher A. Wada. Chapter 1. New York, NY, USA: Routledge.

Rosegrant, M.W., C. Ringler, and T. Zhu. 2014. Water Markets as an Adaptive Response to Climate Change. In K.W. Easter and Q. Huang (eds.), Water Markets for the 21st Century: What Have We Learned? Global Issues in Water Policy 11:35-65. Heidelberg, New York, London: Springer

Rosegrant, M. W., C. Ringler, T. Zhu, S. Tokgoz, and P. Bhandary. 2013. Water and food in the bioeconomy. Challenges and opportunities for development. *Agricultural Economics* 44, supplement 139–150.

Rosegrant, M.W. and the IMPACT Development Team. 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute (IFPRI), Washington, D.C. http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/127162?_ga=1.20075307 0.129622717.1403710257

Rosegrant, M.W., C. Ringler, and T. Zhu. 2009. Water for agriculture: Maintaining food security under growing scarcity. *Annual Review of Environmental Resources* 34:205–222. http://arjournals.annualreviews.org/eprint/T6e4KXUcGtcSNwJxd6pE/full/10.1146/annurev.environ.030308.090351

Rosegrant, M.W. and H. P. Binswanger. 1994. Markets in tradable water rights: Potential for efficiency gains in developing country water resource allocation. *World Development* 22 (11): 1613-1625

Sadoff, C.W., J.W. Hall, D. Grey, J.C.J.H. Aerts, M. Ait-Kadi, C. Brown, A. Cox, S. Dadson, D. Garrick, J. Kelman, P. McCornick, C. Ringler, M.W. Rosegrant, D. Whittington, and D. Wiberg. 2015. Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth, University of Oxford, UK, 180pp.

Wada, Y, L. P. H. van Beek, and M. F. P. Bierkens. 2011. Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability. *Hydrology and Earth System Sciences* 15 (12): 3785–3808.

World Bank 2016. High and Dry: Climate Change, Water, and the Economy. http://www.worldbank.org/en/topic/water/publication/high-and-dry-climate-change-water-and-the-economy

World Bank 2010. World Development Report. Chapter 3. Managing Land and Water to Feed Nine Billion People and Protect Natural Systems. In WDR 2010. Development and Climate Change. World Bank, Washington DC. USA. http://siteresources.worldbank.org/INTWDR2010/Resources/5287678-1226014527953/Chapter-3.pdf

Xie, H., L. You, B. Wielgosz, C. Ringler. 2014. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management* 131: 183-193

Young, M.D. and J.C. McColl. 2009. Double trouble: the importance of accounting for and defining water entitlements consistent with hydrological realities. *The Australian Journal of Agricultural and Resource Economics* 53: 19–35

Young, M. 2015. Unbundling Water Rights: A Blueprint for Development of Robust Water Allocation Systems in the Western United States. NI R 15-01. Durham, NC: Duke University. http://nicholasinstitute.duke.edu/publications.

You, L., C. Ringler, U. Wood-Sichra, R. Robertson, S. Wood, T. Zhu, G. Nelson, Z. Guo and Y. Sun. 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy* 36(6): 770-782