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Satisfying future water demands for agriculture

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ABSTRACT

The global demand for water in agriculture will increase over time with increasing population, rising incomes, and changes in dietary preferences. Increasing demands for water by industrial and urban users, and water for the environment will intensify competition. At the same time, water scarcity is increasing in several important agricultural areas.

We explore several pathways for ensuring that sufficient food is produced in the future, while also protecting the environment and reducing poverty. We examine four sets of scenarios that vary in their focus on investments in rainfed agriculture and irrigation, and the role of international trade in adjusting for national disparities in water endowments. Rainfed agriculture holds considerable potential but requires adequate mechanisms to reduce inherent risks. Irrigation expansion is warranted in places where water infrastructure is underinvested such as sub-Saharan Africa. In South Asia the scope for improving irrigation performance and water productivity is high. International trade can help alleviate water problems in water-scarce areas, subject to economic and political considerations. We examine also a regionally optimized scenario that combines investments in rainfed and irrigated agriculture with strategic trade decisions. Compared to 'business as usual', this scenario reduces the amount of additional water required to meet food demands by 2050 by 80%. Some of that water could be made available for the environment and other sectors. We conclude that there are sufficient land and water resources available to satisfy global food demands during the next 50 years, but only if water is managed more effectively in agriculture.

1. Introduction

The challenges facing agricultural water management today are different from what they were a few decades ago. The global population has grown; people are richer and they demand more agricultural commodities. Also the type of food they consume is shifting towards more meat, fish, dairy, and sugar—products that typically require more water than traditional staple foods such as grains and tuber crops (Molden, 2007). Consequently, agricultural water use has grown substantially and is still increasing. At the same time, urban areas and industrial development claim an increasing share of available water resources. Overexploitation and poor management of water resources threaten the resource base on which agriculture depends. In addition the protection of ecosystems becomes ever more important and urgent (Falkenmark et al., 2007).

Recent forecasts warn of impending global problems unless appropriate action is taken to improve water management and increase water use efficiency (Seckler et al., 1998; Alcamo et al., 1997; Rosegrant et al., 2002, 2005; Shiklomanov, 2000; Vörösmarty et al., 2004; Bruinsma, 2003; SEI, 2005; Falkenmark and Rockström, 2004). Without increases in productivity, an additional 5000 km^3 will be required for crop production to meet future food demands (De Fraiture et al., 2007), while the land area used for crops and cattle will increase by 50–70% (Kemp-Benedict, 2006).

Globally there are sufficient land and water resources to produce food over the next 50 years, but only if water for agriculture is better managed (Molden, 2007). However, at the local and regional scales water scarcity will constrain efforts to increase agricultural production in some of the world's major breadbaskets. Currently about 900 million people live in water-scarce river basins (closed basins), while another 700 million live where the limit to water resources is fast approaching. Yet another 1 billion people live in basins where economic constraints limit the pace of much-needed investments in water management (Molden et al., 2007a).

The policies and investment strategies chosen to increase agricultural production will affect water use, the environment, and the extent and depth of rural and urban poverty. Producing sufficient food to meet future needs will require water develop-

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ment and management strategies that promote improvements in food security while maintaining the productivity of our land and water resources and enhancing environmental amenities (Molden, 2007). Successful strategies can be identified through research and policy analysis pertaining to agronomy, water management, economics, and human welfare.

Scenario analysis can be helpful in examining the potential implications of alternative strategies for achieving food production goals. The procedure involves establishing a baseline projection of future food supply and demand, based on current conditions and expected trends, and comparing the baseline projection with alternative projections that reflect changes in key parameters (exogenous changes) or the adoption of new production methods, new investments, or changes in public policies regarding land use, water allocation, environmental protection, or other pertinent issues (endogenous changes). Scenario analysis is used often to examine alternative futures with respect to long-term goals, such as producing enough food in 2050 to feed the world's population, while also reducing poverty, improving livelihoods, enhancing environmental amenities, and sustaining the productivity of natural resources.

Our goal in this paper is to present the results of such a scenario analysis. We begin by identifying the primary driving forces behind increased demands for water and food. We then explore scenarios based on alternative strategies for meeting these increased demands. The strategies we examine include investing in irrigation, upgrading water management in rainfed areas, and promoting international trade as a measure to offset international disparities in water endowments. We examine also a "regionally optimized" scenario that reflects regional strengths and limitations. For each scenario, we describe pertinent tradeoffs and implications for food production, natural resources, and the environment.

2. Drivers of agricultural water use

By far the most important driver in water use during the coming decades will be the increase and changes in global food demand due to population growth and changes in diet. Although the world's population growth rate is declining, the global population is expected to increase by another 2.5 billion persons before leveling off at around 9 billion by 2050 (UN, 2004). By 2030 two-thirds of the world's population will live in cities. Furthermore, average incomes are expected to grow rapidly, particularly among the growing middle class in fast growing economies such as India and China. As incomes rise, food consumption increases and food preferences adjust toward more nutritious and more diversified diets (Pingali, 2004). Rising incomes throughout much of Asia during the last three decades have led to more consumption of staple cereals, a shift in consumption patterns among cereal crops, and a change in preferences away from cereals toward livestock products and high-value crops by wealthier consumers. For example, in Southeast Asia meat consumption more than tripled, while dairy demand more than doubled from 1961 to 2003. Consumption of high-value crops, such as fruit, sugar, and edible oils also increased substantially (FAOSTAT, 2007). In the years ahead, urbanization and income growth will continue to drive food demand toward higher per capita food intake and richer diets, particularly in low and middle income countries. Such changes influence future agricultural water demand because livestock products, sugar, and oils typically require more water to produce than cereals and roots and tubers.

Food production requires large amounts of water. In some areas, one kilogram of grain requires about 1000 L of water, while estimates of wheat water requirements range from 400 L to more than 5000 L per kilogram of grain. The amount of water required to produce crops varies by crop and region, depending on climate, mode of cultivation (rainfed versus irrigated; high-input versus low-input agriculture), crop variety and length of growing season, and crop yields. Global estimates of annual, total crop water consumption vary between 6800 and 7500 km^3 (Rockström et al., 1999; Postel, 1998; Chapagain, 2006). The Comprehensive Assessment estimate is 7130 km^3. This is roughly equivalent to a depth of 2.17 m of water across the entire land area of India, or 3000 L for each person in the world per day. Water consumed by crops fed to cattle each year is 1312 km^3, or about 18% of the total crop water consumption (Table 1). An additional 840 km^3 (12%) are consumed by grazing livestock.

A large portion of the water consumed by crops, an estimated 78%, comes directly from rainfall that infiltrates the soil to generate soil moisture. The other 22% (1570 km^3) is from surface and groundwater sources. Assuming an estimated delivery efficiency of 60%, 2630 km^3 are withdrawn from surface and groundwater sources and delivered to farm fields to provide the 1570 km^3 of crop water consumption.

Nonfood crops such as cotton occupy 3% of the world's cropped area and 9% of the irrigated area. The demand for cotton is expected to more than double by 2050. Crop production for energy also is increasing in several areas, with potentially substantial implications for land and water use in agriculture (Koplow, 2006). At present less than 2% of the total cropped area is devoted to energy crops and only about 1% of the total water is evaporated by energy crops (De Fraiture et al., 2008). Future production of biofuel crops is uncertain, as is the proportion of the world's water supply that might be needed for this activity. Some countries have established high biofuel targets to counter rising oil prices and alleviate energy

Table 1
Water depletion by sector and crop in km3 in the year 2000.

	Total crop water consumption agriculture	Share from irrigation %	Total crop water consumption cereals[a]	Total crop water consumption feed crops	Water depleted for Grazing[b]	Total withdrawals for irrigation	Total withdrawals for domestic and industrial	Water consumption of biomass for energy[c]	Water consumption for biofuels crops[d]
Sub-Saharan Africa	1071	6	557	68	218	68	10	149	
East Asia	1661	22	960	277	96	518	99	139	14[e]
South Asia	1505	41	896	16	27	1095	34	102	8[f]
Central Asia and Eastern Europe	772	20	525	277	61	244	156	27	
Latin America	895	12	336	190	240	175	52	84	4[g]
Middle East and North Africa	225	61	166	59	13	173	24	4	
OECD countries	990	17	640	426	185	233	519	27	32[h]
World	7130	22	4089	1312	840	2630	877	535	104

Source: De Fraiture et al. (2007).

[a] Includes cereals used for feed; [b] refer to Kemp-Benedict (2006a); [c] includes all biomass (mostly firewood) refer to Kemp-Benedict (2006b); [d] includes biofuels used in transport, values for 2003, refer to De Fraiture et al. (2008); [e] China; [f] India; [g] Brazil; [h] USA and EU.

security concerns. For example, India aims to derive 20% of its transport fuels from crops or agricultural residues by 2017. In other countries recent increases in food prices, environmental concerns, and food security scares have tempered the initial optimism regarding the role of bioenergy. For example, the European Union recently capped the share of transport fuels coming from crops at 6%.

The potential impact of the increasing demand for bioenergy on agricultural water use is large. The water footprint of energy derived from biological sources is 40–70 times larger than that of fossil fuels (Gerbens-Leenes et al., 2008). To produce one liter of biofuel from crops requires evaporation of between 2500 and 3500 L (De Fraiture et al., 2008). This is about the same as the evapotranspiration required to produce the daily food consumption for one person (i.e., 3000 L). Water requirements are smaller for "second generation" biofuels derived from grasses and trees, and for fuels based on non-food crops such as jatropha, pongamia and sweet sorghum (Rajagopal, 2008). However, additional research is needed regarding the water productivity of non-traditional crops (Jongschaap et al., 2007).

Estimates of future water use for bioenergy vary by an order of magnitude from 1000 km^3 (lowest scenario in Berndes, 2002) to 11,700 km^3 (highest scenario in Lundqvist et al., 2007) of which a considerable portion is met by non-crops (grasses, trees and waste). Due to the high degree of uncertainty regarding water requirements for biofuels, we do not consider bioenergy production formally in our scenarios. We note also that much of the current demand for biofuels is driven by national policy choices that involve subsidies for producers of biofuel crops and refiners of biofuel products. Sharp changes in policy focus might cause large changes in the supply and demand for biofuels in future, with consequently large swings in the amount of water required in the production and processing of biofuel crops.

Without improvements in land and water productivity or major shifts in production patterns, the amount of crop water consumption in 2050 must increase by 70–90%, depending on actual growth in population and income, and assumptions regarding the water requirements of livestock and fisheries. If that occurs, crop water consumption would reach between 12,050 and 13,500 km^3, up from 7130 km^3 today (Molden et al., 2007a). This estimated range includes crop water depletion for food and feed production, plus losses through evaporation from soil and open water. Evaporation from flooded rice paddies, irrigation canals, and reservoirs also is included, while evaporation from grasslands and aquaculture ponds is not. While these estimates reflect 'business as usual' conditions, even with improvements in water productivity, agriculture will continue to consume a large portion of the world's developed water supply.

3. Major pathways to meet future food demand

The policies and investment strategies chosen to increase food production will affect water use, the environment, and the extent and depth of rural and urban poverty. Feeding three billion more people by 2050 will require water management and development strategies that promote improvements in food security while maintaining the productivity of our land and water resources and enhancing natural ecosystems. Four broad strategies include:

a) Investing to increase production in *rainfed agriculture*.

We can improve productivity by enhancing soil moisture management and providing supplemental irrigation in areas where small water storage facilities are feasible. We can also expand the size of cropped areas in rainfed regions.

b) Investing in *irrigated agriculture*.

We can increase annual irrigation water supplies by innovating system management, developing new surface water storage facilities, increasing groundwater withdrawals, and promoting the use of wastewater. We can also increase water productivity in irrigated areas and increase the value per unit of water by integrating multiple uses – including livestock, fisheries, and domestic use – in irrigated systems.

c) Promoting *agricultural trade*.

We can describe opportunities for trading agricultural products from water abundant and highly productive areas to water-short areas. Such a strategy might be helpful in offsetting disparities in national water endowments when the economic, political, and social implications of such trading arrangements are complementary.

d) Limiting the potential increase in world *food demand*.

We can influence diets through advertising campaigns and appropriate pricing of foods to reflect the scarce resources used in food production. We can also reduce post-harvest losses by improving transportation infrastructure, enhancing market access, and improving industrial and household processes to reduce waste.

Each of these strategies will impact water use, the environment, and the poor in different ways. Enhanced agricultural production from rainfed areas and higher water productivity in irrigated areas can reduce the need for developing additional water resources (Molden et al., 2000; Rosegrant et al., 2002; Rockström, 2003). But the potential of rainfed agriculture and the scope for improving water productivity in irrigated areas is debated (Seckler et al., 2000; Rosegrant et al., 2002; Kijne et al., 2003). Trade can help mitigate water scarcity if water-short countries import food from water abundant countries (Hoekstra and Hung, 2005). But political and economic factors may limit the scope and potential of such trading arrangements (De Fraiture et al., 2004; Wichelns, 2004).

Investments in rainfed and irrigated agriculture will help alleviate rural poverty, particularly in SSA (Castillo et al., 2007; Faurès et al., 2007), but irrigated area expansion may have serious consequences for the environment (Falkenmark et al., 2007). Reducing losses that occur in the food chain (i.e., from farmers' fields to consumers' plates) will help reduce food demand and thus reduce the amount of water used in agriculture. However, many actors are involved in the food chain and, hence, improving efficiency may prove challenging (Lundqvist et al., 2008). Prevailing views of the most appropriate future pathways diverge strongly, as reflected in previous water use forecasts (Table 2). Seckler et al. (2000) project a relatively small increase in rainfed cereal production (0.19% per year), while projecting notably large increases in irrigated areas and crop yields (0.95% and 1.14% per year, respectively). By contrast, Rosegrant et al. (2002) project a 1.14% annual increase in both rainfed cereal production and irrigated crop yields, and a 0.36% annual increase in irrigated area. These authors project that cereal trade will increase by 2.41% per year, while Seckler et al. (2000) project only a 0.64% annual increase in cereal trade. The potential implications of these alternative projections on resource use and incomes can be substantial.

4. Scenario analysis

We generate scenarios to illustrate and quantify the potential implications of the four investment strategies described above. Our primary simulation tool is the WATERSIM model (De Fraiture,

Table 2
Comparison of recent global water use forecasts.

Author	Projection period	Increase in rainfed cereal production annual growth rate	Increase in irrigated yield annual growth rate	Increase in irrigated harvested area annual growth rate	Increase in cereal trade annual growth rate	Increase in agricultural water withdrawals annual growth rate
Shiklomanov (2000)	1995–2025			0.74%		0.68%
Seckler et al. (2000)	1995–2025	0.19%	1.13%	0.95%	0.64%	0.56%
Rosegrant et al. (2002)	1995–2025	1.14%	1.14%	0.36%	2.41%	
Faurès et al. (2002)	1995–2030	1.10%	1.00%	0.95%	2.08%	0.43%
Alcamo et al. (2005)	2000–2050			0.06–0.18%	1.85–2.44%	0.40–1.22%
De Fraiture et al. (2007)	2000–2050	0.63–1.03%	0.58–1.15%	0–0.56%	0.98–2.01%	0.10–0.90%

2007), which consists of two fully integrated modules: a food production and demand module based on a partial equilibrium model, and a water supply and demand module based on a water balance and accounting framework. To adequately capture: 1) hydrologic processes at the basin scale, and 2) economic phenomena at the country scale, the model includes 282 hybrid units intersecting 128 hydrological units with 115 socio-economic units (i.e., countries and country groups). This degree of detail enables us to examine opportunities and limitations regarding productivity enhancement and area expansion effectively, as the scope and feasibility of alternative strategies vary by region.

We model productivity growth as a function of the exploitable yield gap; i.e., the difference between the maximum attainable yield and yields that are actually achieved. Specifically, in an optimistic scenario we assume that 80% of the yield gap is bridged by 2050, while in a pessimistic scenario we assume that only 20% is bridged. The rates of growth in productivity in our scenarios are higher in areas where the current yield gap is large, such as in sub-Saharan Africa, than in areas where the current yield gap is small, such as in OECD countries (Fig. 1).

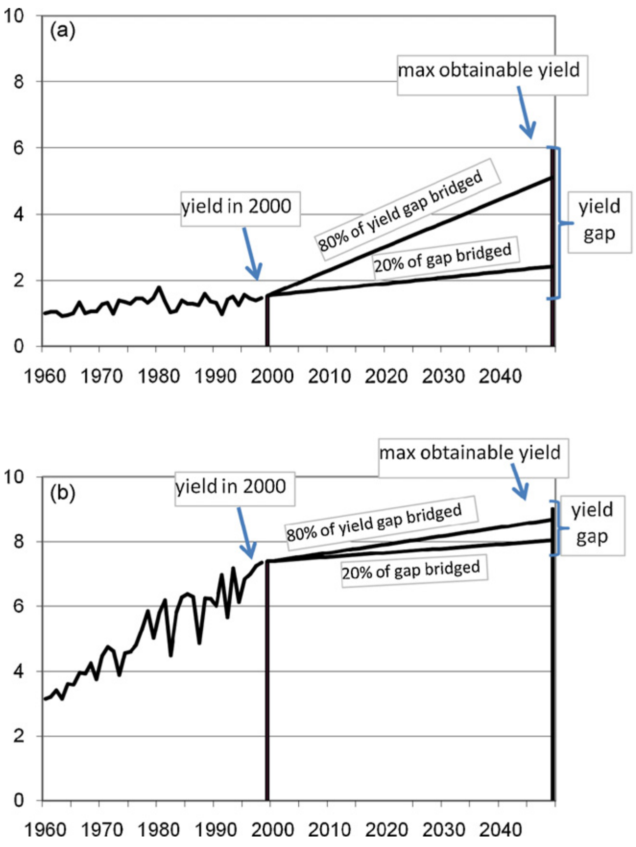

Fig. 1. (a) Actual and maximum obtainable maize yields in sub-Saharan Africa, in tonnes/ha. (b) Actual and maximum obtainable maize yields in OECD countries, in tonnes/ha.

We obtain our estimates of maximum attainable yields from the Global Agro Ecological Zones (GAEZ) methodology (Fischer et al., 2002; Bruinsma, 2003), which uses physical and crop management factors to establish maximum levels of productivity on a grid-cell basis. The maximum attainable yield assumes production of the most suitable varieties with high-input levels, with adjustments for land quality. This approach provides realistic estimates based on known techniques, without assuming major breakthroughs. We determine the potential for crop area expansion using GAEZ land suitability classes. In particular, we assume that expansion is limited to lands in classes 'suitable' and 'very suitable' for agriculture.

Within our scenarios, food demand is a function of population growth (UN, 2004), income projections (done as part of the Millennium Ecosystem Assessment, MEA, 2005) and food demand elasticities, borrowed from the IMPACT model (Rosegrant et al., 2002). In the global food module, regions are linked through food commodity trade, which is the difference between domestic production and demand for each region. Regions with positive trade balances in a commodity are net exporters of that good, while those with negative balances are net commodity importers.

At the sub-basin level, water availability is simulated using a water balance approach based on the water accounting concepts developed by Molden (1997). Sub-basins are connected in such a way that outflow from upstream becomes inflow into the lower sub-basin. When water supply falls short of demand, the shortages are distributed over months, sectors and crops using an optimization model and allocation rules. Water shortages lead to reductions in productivity and smaller harvested areas. Data are derived from the IWMI Water and Climate Atlas,[1] Mitchell et al. (2004), AQUASTAT database (FAO, 2005), and runoff is computed using the global hydrologic model WaterGap (Alcamo et al., 1997). The model computes total food production, the area under rainfed and irrigated conditions, water diversions to agriculture and crop water consumption at the basin and national scales (De Fraiture, 2007). World prices for food are endogenous to the system of equations that represent the underlying food production and consumption relationships and are not considered explicitly in the scenarios.

We conducted our scenario analysis as part of the Comprehensive Assessment of Water Management in Agriculture (Molden, 2007). Our results indicate that growth in global water diversions to agriculture by 2050 varies from 5% to 57% depending on assumptions regarding trade, water use efficiency, area expansion, and productivity growth in rainfed and irrigated agriculture (De Fraiture et al., 2007). Increases in cropped area vary from 5% to 38% (Table 3 and Fig. 2).[2] We describe the background, rationale, and results of our scenario analysis in the following paragraphs.

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[1] http://www.iwmi.cgiar.org/WAtlas/Default.aspx.

[2] This range is computed by adding rainfed and irrigated areas (340 m ha plus 860 m ha in 2000, versus 340 m ha plus 920 m ha in the optimistic rainfed scenario and 340 m ha plus 1320 m ha in the pessimistic rainfed scenario).

Table 3
Overview of scenarios of rainfed, irrigation and trade in 2050.

	Base year (2000)	Rainfed scenarios (2050)		Irrigation scenarios (2050)		Trade scenario (2050)	Optimistic scenario (2050)
		High yield	Low yield	Area expansion	Yield improvement		
Rationale		Emphasis on investments in rainfed areas: water harvesting and supplemental irrigation	Simulates the pessimistic case where upgrading rainfed is not successful	Emphasizes food self-sufficiency and stable food supply through expansion of irrigated areas	Emphasis on improving performance of existing irrigated areas: increase in yield and water productivity	Agricultural trade from water abundant countries to water-scarce countries	An optimistic, but plausible, scenario that emphasizes optimal strategies that vary among regions
Irrigated area in million ha	340	340	340	450	370	340	394
% growth		zero	zero	+33%	+9%	zero	+16%
Rainfed area (million ha)	860	920	1320	1100	1140	1040	920
% growth		+7%	+53%	28%	+33%	+22%	+7%
Irrigated cereal yield (metric tonnes per ha)	3.70	5.02	4.94	5.04	6.55	4.94	5.74
% growth		+34%	+30%	+35%	+77%	+33%	+55%
Rainfed cereal yield (metric tonnes per ha)	2.46	4.24	2.96	2.95	2.97	3.90	3.88
% growth		+72%	+20%	+20%	+20%	+59%	+58%
Water productivity irrigated (kg per m^3)	0.68	0.84	0.83	0.83	0.97 + 43%	0.83	1.01
% growth		+23%	+22%	+22%		+22%	+48%
Crop water consumption directly from rainfall (km^3)	5560	7415	9040	8080	7880	7260	6570
% growth		+33%	+63%	+45%	+42%	+31%	+19%
Crop water consumption from irrigation deliveries (km^3)	1570	1870	1870	2420	2255	1650	1945
% growth		+19%	+19%	+54%	+44%	+5%	+24%
Withdrawals for irrigation (km^3)	2630	3155	3160	4120	3460	2760	2975
% growth		+19%	+19%	+57%	+32%	+5%	+13%

Source: De Fraiture et al. (2007).

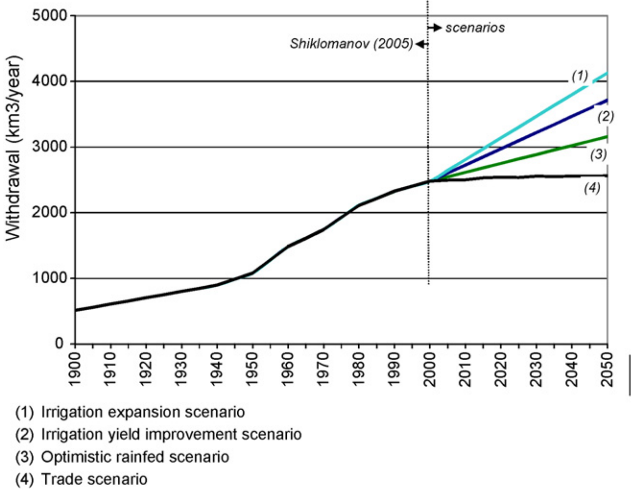

Fig. 2. Past and future global water diversions under different scenarios.

4.1. The potential role of rainfed agriculture

Millions of poor farmers in developing countries depend on rainfed agriculture to support their livelihoods. There are large areas of rainfed agriculture also in industrialized countries, where crop yields are considerably higher. In aggregate, rainfed agriculture currently plays a dominant role in producing the world's food supply. About 62% of the gross value of the world's food is produced under rainfed conditions on 71% of the world's cropland. However, the proportion of future food production that could or should come from rainfed or irrigated agriculture is the subject of debate.

There are several compelling reasons to invest in water management in rainfed agriculture (Molden, 2007). First, actual yields are low and there is a large, untapped potential to increase productivity, particularly in sub-Saharan Africa, where many of the rural poor depend on rainfed agriculture rather than irrigated agriculture. Second, investment costs in rainfed areas tend to be lower than in irrigated agriculture, also particularly in SSA. Third, irrigation development has high environmental and social costs (such as fragmentation of rivers and wetlands, water scarcity, waterlogging and salinization, and displacement of residents to make way for large reservoirs).

Rockström et al. (2007) argue that upgrading rainfed areas through investments in soil and water conservation, water harvesting techniques and supplemental irrigation can double or even quadruple productivity in drought-prone tropical regions. Many observers might agree that improving water management in rainfed areas, although traditionally neglected, is essential for increasing agricultural productivity.

Nevertheless, the potential role of rainfed agriculture in contributing to world food production is a subject of debate, and forecasts regarding the relative roles of irrigated and rainfed agriculture vary considerably. Rosegrant et al. (2002) project that more than 50% of additional grain production will come from rainfed areas, particularly in developed countries, while developing countries will increase their imports of grains. The Food and Agriculture Organization foresees that the contribution to global food supply from rainfed areas will decline from 65% today to 48% in 2030 (Bruinsma, 2003), due partially to productivity improvements and irrigated area expansion.

Referring to mixed results of past efforts to enhance productivity in rainfed areas, Seckler et al. (2000) are less optimistic concerning the potential of rainfed areas. They foresee that only 5%

Table 4
Rainfed scenario results.

	Rainfed cereal yield 2000 (tonnes/ha)	Rainfed cereal yield optimistic 2050[*] (tonnes/ha)	Rainfed cereal yield pessimistic 2050[*] (tonnes/ha)	Rainfed harvested area 2000 (million ha)	Rainfed harvested area optimistic 2050[**] (million ha)	Rainfed harvested area pessimistic 2050[**] (million ha)	Crop water consumption 2000 (billion m^3)	Crop water consumption optimistic scenario 2050[***] (billion m^3)	Crop water consumption pessimistic scenario 2050[***] (billion m^3)
Sub-Saharan Africa	1.0	3.1	1.6	158	169	252	1080	1350	1837
Middle East and North Africa	0.8	1.4	1.0	18	22	23	233	286	282
Central Asia Eastern Europe	2.0	3.7	2.5	128	111	206	780	834	1202
South Asia	1.3	2.9	1.9	98	110	126	1479	1922	1901
East Asia	2.6	4.8	3.3	156	187	243	1670	2308	2369
Latin America	2.5	4.4	2.9	101	144	245	905	1443	2057
OECD	4.7	6.6	5.2	172	173	213	980	1115	1235
World	2.5	4.2	2.9	860	920	1320	7130	9285	10910

[*] Projected yields are based on the yield gap (i.e., difference between maximum attainable (GAEZ) and actual yields). The optimistic scenario assumes that 70–80% of the gap will be bridged; the pessimistic scenario foresees that only 20–25% will be bridged.

[**] The area needed to meet all future food demand with projected yield increases. Irrigated area remains at the same level as in the baseyear.

[***] Includes crop water consumption met by rainfall and irrigation.

of the increase in future grain production will come from rainfed agriculture, while the major portion will originate from irrigated areas.

Relying on rainfed agriculture as a major source of food production carries risks. Most water harvesting techniques are useful for bridging short dry spells, but longer dry spells can lead to total crop failure. Further, while numerous case studies document the benefits of upgrading rainfed agriculture, achieving such results more broadly, throughout one or more production regions remains challenging (AfDB et al., 2007). Water harvesting techniques have been implemented in some areas for many years, but adoption rates have been low, due to the limited profitability of agriculture, the lack of markets, relatively high labor costs, and high risks. Efforts to alleviate these concerns will be needed to promote broader adoption of water harvesting techniques.

To contrast the optimistic and pessimistic views regarding the potential of rainfed agriculture and to assess the inherent risks, we examine two rainfed scenarios (De Fraiture et al., 2007). In our high yield (optimistic) scenario we assume that prices and incentives are correct and that the necessary physical and institutional arrangements are in place (markets, roads, extension services and credit facilities). In our low yield (pessimistic) scenario we assume that adoption rates of water harvesting measures and supplemental irrigation are low. Our analysis of these scenarios demonstrates that upgraded rainfed agriculture can produce the food required in future (Table 4), but there are conditions that must be met.

Experience indicates that the required productivity increases will not occur without substantial investments in water harvesting, agricultural research, supporting institutions and rural infrastructure. In addition, crop yields will vary with economic incentives and crop prices, as farmers will respond to those parameters when choosing key inputs. Our optimistic, high yield scenario will evolve only if generating high yields is profitable for farmers (Bruinsma, 2003). Our pessimistic, low yield scenario shows that when appropriate incentives are missing, 53% more crop water consumption and 38% more land are needed to achieve food production goals (Table 4).[3] Such large increases in crop water consumption will likely impact downstream ecosystems and water users due to reduced stream flows. The large expansion of agricultural land will negatively impact biodiversity and ecosystem services.

4.2. The potential role of irrigated agriculture

Like rainfed agriculture, irrigated agriculture also plays a major role in food production, and also provides livelihoods for millions of poor farmers in developing countries. Irrigated agriculture currently provides 40% of the global cereal supply (60% of the cereals produced in developing countries). Worldwide, about 38% of the gross value of production comes from irrigated areas, which make up 29% of the harvested area. Many observers expect that the contribution of irrigated agriculture to food production and rural development will increase in the coming decades (Bruinsma, 2003; Seckler et al., 2000).

Perceptions of the costs and benefits of irrigation have changed markedly during the past 50 years (Faurès et al., 2007), contributing to a decline in public investments in irrigation during the 1990s. After a decade of decline, the last few years have seen an increasing interest in public funding in water infrastructure for agriculture, particularly in Asia and in sub-Saharan Africa, where irrigation development is limited and the potential for improving access to irrigation water remains large. Reasons for the renewed interest include concerns regarding climate change induced rainfall variability; maintaining the existing infrastructure; potential for poverty alleviation; the high potential to improve performance (Faurès et al., 2007), and the recent concerns regarding food prices and availability.

Our scenario analysis demonstrates the substantial potential for improving performance in existing irrigated areas, particularly in South Asia, where more than 50% of the harvested area is irrigated and yields are low. Three quarters of the additional food supply by 2050 can be met by improving the productivity of existing irrigated areas (Table 5). In South Asia all of the additional cereal demand can be met through irrigated yield improvements, though this would require additional water withdrawals. In other areas, such as the Middle East and North Africa (MENA) region and OECD countries, where yields are already quite high, the potential is much smaller.

Improving irrigation performance (i.e., increasing water productivity) is by no means easy (Molden et al., 2007b). Technical assistance, capacity building, and the right incentives and policies are required to motivate farmers to increase water productivity.

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[3] The percentage increase in land is computed by adding rainfed and irrigated land areas (340 m ha plus 860 m ha in 2000 versus 340 m ha plus 1320 m ha in 2050). The increase in crop water consumption includes water consumption from rainfall and irrigation water (9040 km^3 plus 1870 km^3 in 2050 versus 5560 km^3 plus 1570 km^3 in 2000).

Table 5
Irrigation scenario results.

	Irrigated cereal yield 2000 (tonnes/ha)	Irrigated cereal yield 2050 YI-scenario* (tonnes/ha)	Irrigated cereal yield 2050 AR-scenario* (tonnes/ha)	Irrigated harvested area 2000 (million ha)	Irrigated harvested area 2050 YI-scenario** (million ha)	Irrigated harvested area 2050 AR-scenario** (million ha)	Irrigation withdrawals 2000 (billion m^3)	Irrigation withdrawals 2050 YI-scenario (billion m^3)	Irrigation withdrawals 2050 AR-scenario (billion m^3)
Sub-Saharan Africa	2.2	5.6	3.1	6	7	13	72	110	159
Middle East and North Africa	3.5	6.8	4.4	19	21	26	181	273	279
Central Asia Eastern Europe	3.4	7.2	4.2	33	34	37	256	347	333
South Asia	2.7	5.4	4.1	104	115	135	1150	1491	1817
East Asia	4.0	6.8	5.7	116	122	169	544	694	927
Latin America	4.0	7.6	5.5	17	19	23	184	268	304
OECD	6.6	9.0	7.2	45	45	50	245	274	303
World	3.7	6.5	5.0	341	363	454	2631	3460	4121

* The YIELD-scenario emphasizes improvements of land and water productivity in existing irrigation schemes; the AREA-scenario focuses on irrigated area expansion. The projected yields are based on the irrigated yield gap (i.e., difference between maximum attainable (GAEZ) and actual irrigated yields). The YIELD-scenario assumes that 70–80% of the irrigated yield gap will be bridged; the AR-scenario foresees that only 20–25% will be bridged.

** Under the AREA-scenario the irrigated area grows by 0.6% annually at about the same pace as over the past 30 years; under the YI-scenario.

Expanding irrigated areas will improve farm-level access to water, increase farm incomes, and enhance food security. By expanding the irrigated area by 33%[4] irrigation could contribute 55% of the total value of food supply by 2050. But this gain might come with high financial and environmental costs, particularly in areas that are already water scarce. In our irrigation expansion scenario, water withdrawals for agriculture increase by 40%, posing a threat to aquatic ecosystems and capture fisheries. In much of sub-Saharan Africa, where irrigation development is limited, expansion seems warranted. Starting from a low base, and doubling the irrigated area in sub-Saharan Africa, would increase irrigation's contribution to food supply from only 4% today to an optimistic 11% by 2050.

4.3. The role of trade: virtual water, can it work in reality?

Because the production of agricultural commodities requires large amounts of water, expanded international food trade can have significant impacts on water demands at the national level. Allan (1998) coined the term 'virtual water' to denote the water used to produce crops that are traded internationally. By importing agricultural commodities, a nation 'saves' the amount of water it would have required to produce those commodities in country (Hoekstra and Hung, 2005). For example, Egypt, a highly water stressed country, imported 8 million tonnes of grain from the United States in 2000. To produce this amount of grain, Egypt would have needed about 8.5 billion m^3 of irrigation water—one sixth of the annual releases from the Lake Nasser. At the global level, cereal trade has a moderating impact on irrigation water demands, as four of the five major grain exporters (USA, Canada, France, Australia and Argentina) produce grain in highly productive rainfed conditions. Major importers, such as Egypt, Mexico, Iran, Saudi Arabia, and Algeria, rely on irrigation to produce grains. In 1995, without cereal trade, global irrigation water demand would have been higher by 11% (De Fraiture et al., 2004; Oki et al., 2003).

International food trade could thus contribute to mitigating water scarcity problems. To assess the potential of trade as a water saving mechanism we formulate the 'ideal virtual water trade' scenario in which countries with abundant water resources and production capacities increase their agricultural production and export agricultural commodities to water-short countries. North America, Latin America (mainly Brazil and Argentina), Northwest Europe, and Eastern Europe (Russia and Ukraine) export to the Middle East and North Africa and to India, Pakistan, and China. Sub-Saharan Africa improves its rainfed agriculture, but remains a minor importer.

In the importing countries, crop yields improve at a modest pace (25% between now and 2050), while the sizes of irrigated and rainfed areas remain constant. Water-short areas in China, India, the Middle East and North Africa reduce their irrigated areas for cereals, shifting toward labor intensive, higher valued crops such as vegetables. In exporting countries rainfed yields of staple crops – such as cereals, soybeans (oil crops), and roots and tubers – improve by an average 60% between now and 2050. Rainfed areas in exporting countries increase by 260 million hectares. Much of the expansion occurs in Latin America, where the scope for area expansion is still large.

Our scenario analysis reveals that, in theory, world food demands can be satisfied through international trade, without worsening water scarcity or requiring additional irrigation infrastructure (Table 6).

A portion of agricultural trade is already driven by water scarcity and constraints pertaining to land and labor availability. However, it seems unlikely that water concerns will be a primary driver of increased trade volumes in the near term, given the roles that socio-economics, politics, and public policies play in determining trade patterns. For example, many low-income countries struggling with food security remain wary of depending on imports to satisfy basic food needs. Food imports must be paid for with foreign exchange currency, which is earned by selling exports or obtained through grants and loans (Seckler et al., 2000). Many poor countries, particularly in sub-Saharan Africa, do not have sufficient exports to pay for imports, and recent hikes in food and energy prices have further worsened the trade balance of countries dependent on food imports. Several countries have modified their views regarding food imports and domestic food production in response to recent changes in food prices and availability on international markets. For example, when rice, wheat and maize prices soared in the first half of 2008, large exporters such as Viet Nam, Thailand and India responded by restricting exports, citing concerns regarding national food supplies.

International trade provides water-short nations an option for responding to increasing water scarcity. The importance of this option in future will depend on many factors, including the costs of engaging in trade, international trade agreements, and the nature

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[4] The irrigated area grew by 0.6% annually during the past 20 years. Extending this trend to 2050 will result in a further increase in irrigated area of 35%.

Table 6
Trade scenario results.

	Cereal demand 2000 (million metric tonnes)	Cereal demand 2050 (million metric tonnes)	Net cereal trade 2000* (million metric tonnes)	Net cereal trade 2050* (million metric tonnes)	Net trade as percentage of demand 2000 (%)	Net trade as percentage of demand 2050 (%)	Irrigation withdrawals 2000 (billion m^3)	Irrigation withdrawals 2050 (billion m^3)
Sub-Saharan Africa	98	213	−14	−51	14%	24%	72	74
Middle East and North Africa	99	208	−51	−156	52%	75%	181	181
Central Asia Eastern Europe	234	295	8	181	3%	61%	256	251
South Asia	241	478	16	−119	7%	25%	1150	1275
East Asia	505	807	−25	−191	5%	24%	544	552
Latin America	149	290	−16	178	11%	61%	184	189
OECD	508	582	121	136	24%	23%	245	246
World	1840	2880	145**	495**	8%	17%	2631	2768

* Trade between the 7 regions without accounting for trade between countries within the region; negative values indicate imports.
** Sum of cereal exports.

of domestic economic objectives and political considerations (Wichelns, 2004). The implication is that given the present global and national geopolitical situation, it is unlikely that trade alone will solve water scarcity.

4.4. Reducing gross food demand

The food requirements of diets based on meat from grain-fed cattle may require twice the water required to support vegetarian diets. A diet without meat requires an estimated 2000 L per day to produce, while a diet high in grain-fed beef requires 5000 L of water (Renault and Wallender, 2000). Thus, the potential to reduce pressure on water resources by changes in food consumption patterns seems high. For example, in the four scenarios used by the Millennium Ecosystem Assessment, meat consumption varies from 41 to 70 kg per person per year, depending on income, price, and public perceptions about health and environment (Alcamo et al., 2005). In the high meat consumption scenario, global agricultural water consumption is 15% (or 950 km^3) higher than in the high vegetable consumption scenario. However, measures and policies to change diets are notoriously difficult to implement and sometimes controversial. Most of the discussion on how to reduce pressure on water resources has focused on producers rather than consumers of agricultural products (Lundqvist et al., 2007).

A more promising pathway to reduce total food demand – and therefore total water demand – might be to minimize losses that occur in the food production and marketing chain. While estimates are sketchy and rather outdated, available evidence points to a considerable amount of agricultural produce lost in the steps between production and consumption. Estimates vary between 40% and 50% (Lundqvist et al., 2008). There are several stages in the food chain where substantial losses occur. For example, losses in the field (between planting and harvest) may be as high as 20–40% of the potential harvest in developing countries due to pests and pathogens (Kader, 2005). Losses in processing, transport, and storage are conservatively estimated between 10% and 15% in quantity terms, but could range from 25% to 50% of the total economic value, due to reductions in food quality (Kader, 2005). Lastly, substantial losses occur during retail sales and consumption, due to the discarding of excess perishable products, product deterioration, and food not consumed. In the United States about 25% of fresh fruit and vegetables are not consumed, although some of the produce is used for animal feed or compost. In developing countries an estimated 10% of fruit and vegetables are not consumed (Kader, 2005).

Despite uncertainties inherent in these estimates, the order of magnitude suggests considerable potential for increasing net productivity in the food chain and thereby reducing future food demands and water requirements. However, improving net productivity in the food chain will not be easy. There are many steps and many actors involved in moving food from fields to households, such as farmers, agricultural workers, truck drivers, shopkeepers, government officials and consumers. Where waste in individual steps is small, the costs and efforts to improve net productivity could outweigh the potential benefits for individual producers and consumers. Hence public programs and incentives might be needed to motivate socially desirable reductions in crop losses and food waste.

4.5. A regionally optimized scenario

Opportunities for improving agricultural productivity and expanding irrigated areas differ by region (Table 7). In general, water scarcity constrains further irrigation expansion in much of the Middle East and North Africa, and the scope for rainfed agriculture there is limited. In South Asia land is becoming a constraint, and water scarcity problems are also increasing. China has sufficient water in the South but not in the North where most agricultural areas are located. In Latin America and most of sub-Saharan Africa, land and water are still plentiful but investment levels have been low. In South Asia 60% of the harvested area is irrigated and the gap between attainable and actual yields is large. The scope for augmenting food supplies and increasing rural incomes by improving yields is high. By contrast in sub-Saharan Africa less than 4% of the harvested area is irrigated. While the yield gap in irrigated areas is high, bridging this gap will have a relatively small impact on total food supply, as the irrigated area is small. Livelihoods might be improved more effectively by investing in activities that upgrade agricultural production in rainfed areas.

We formulate a "regionally optimized" scenario that combines positive elements from the scenarios above and accounts for

Table 7
Regional scope for productivity improvement and area expansion.

	Scope for improved productivity in rainfed areas	Scope for improved productivity in irrigated areas	Scope for expansion of irrigated area
Sub-Saharan Africa	High	Some	High
Middle East and North Africa	Some	Some	Very limited
Central Asia Eastern Europe	Some	Good	Some
South Asia	Good	High	Some
East Asia	Good	High	Some
Latin America	Good	Some	Good
OECD	Some	Some	Some

Table 8
A regionally optimized scenario, results.

	Irrigated water productivity cereals 2050 (kg/m^3)	Cumulative change (%)	Rainfed water productivity cereals 2050 (kg/m^3)	Cumulative change (%)	Crop water consumption 2050 (billion m^3)	Cumulative change (%)	Irrigation withdrawals 2050 (billion m^3)	Cumulative change (%)
Sub-Saharan Africa	0.50	58	0.28	75	1379	29	100	46
Middle East and North Africa	0.82	41	0.25	47	272	7	228	8
Central Asia Eastern Europe	1.05	43	0.69	47	773	0	271	11
South Asia	0.79	62	0.46	82	1700	15	1195	9
East Asia	1.06	45	0.57	36	1990	19	601	16
Latin America	0.91	52	0.63	50	1361	52	196	12
OECD	1.42	18	1.30	25	1021	4	238	2
World	0.93	38	0.64	31	8515	20	2975	13

regional opportunities and constraints.[5] Broadly speaking this scenario emphasizes irrigation performance improvements in South Asia, with modest area expansion. Irrigation is reduced in areas with notable groundwater overdraft. In sub-Saharan Africa the irrigated area increases by 80%, but most of the additional production comes from rainfed agriculture, including areas with supplemental irrigation. In the Middle East and North Africa region water withdrawals and groundwater water overdraft are reduced, and environmental flow regulations strictly adhered to, even if the area under irrigation needs to be reduced. The area in irrigated cereals is reduced in favor of high-value crops (fruits and vegetables) and cereal imports increase substantially. Eastern Europe, Central Asia and Latin America expand cultivated areas, mainly under rainfed conditions. Globally, rainfed yields increase by 58% and irrigated yields increase by 55%, given the assumptions in our scenarios regarding the annual rates of increase in productivity. This scenario shows that by 2050, even with optimistic assumptions regarding productivity growth, crop water consumption increases by 20% (8515 km^3 in 2050 versus 7130 km^3 in 2000) while water withdrawals for agriculture increase by 13% (2975 km^3 in 2050 versus 2630 km^3 in 2000) (Table 8).

5. Conclusion

Globally there are sufficient land and water resources to produce food for a growing population during the next 50 years.

The key for producers, scientists, and public officials is to determine the best investments and strategies for achieving food production goals, given the implications of alternative choices. The available investments and strategies will have different impacts on land and water resources, ecosystems, and the extent and depth of rural and urban poverty. For example, upgrading rainfed agriculture can contribute notably to increasing household incomes in many poor regions, but annual production will vary with changes in rainfall. Expanding irrigated areas can generate more reliable increases in annual output, but expansion opportunities are limited in many parts of Asia and North Africa due to water constraints. There is substantial scope for expanding irrigated areas in sub-Saharan Africa where historical investments have been small, but investments in complementary inputs, infrastructure, and market access also will be needed to maximize agricultural productivity. Similar investments will improve productivity in both rainfed and irrigated agriculture in many regions.

The regionally optimized scenario we present demonstrates that much of the additional demand for food in 2050 can be achieved through productivity increases. In this scenario, as in others, water consumption and withdrawals for agriculture increase over time. The challenge is to manage this increase in a way that minimizes adverse impacts on ecosystems and contributes to reducing poverty, while providing the necessary increase in global food production.

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[5] The regionally optimized scenario does not include reductions in gross food demand because of the lack of reliable estimates and the high levels of uncertainty involved.

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