Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080

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Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080

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Abstract

Potential changes in global and regional agricultural water demand for irrigation were investigated within a new socio-economic scenario, A2r, developed at the International Institute for Applied Systems Analysis (IIASA) with and without climate change, with and without mitigation of greenhouse gas emissions. Water deficits of crops were developed with the Food and Agriculture Organization (FAO)–IIASA Agro-ecological Zone model, based on daily water balances at 0.5° latitude × 0.5° longitude and then aggregated to regions and the globe. Future regional and global irrigation water requirements were computed as a function of both projected irrigated land and climate change and simulations were performed from 1990 to 2080. Future trends for extents of irrigated land, irrigation water use, and withdrawals were computed, with specific attention given to the implications of climate change mitigation. Renewable water-resource availability was estimated under current and future climate conditions. Results suggest that mitigation of climate change may have significant positive effects compared with unmitigated climate change. Specifically, mitigation reduced the impacts of climate change on agricultural water requirements by about 40%, or 125–160 billion m^3 (Gm^3) compared with unmitigated climate. Simple estimates of future changes in irrigation efficiency and water costs suggest that by 2080 mitigation may translate into annual cost reductions of about 10 billion US$.

Keywords: Water; Agriculture; Irrigation; Climate change; Mitigation

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1. Introduction

Water is a key driver of agricultural production and its most precious input. Since the very beginning of plant cultivation, over 10,000 years ago, irrigation water has enabled farmers to increase crop yields by reducing their dependence on rainfall patterns, thus boosting the average crop production while decreasing the interannual variability [1,2]. Today, the irrigated area has expanded to over 270 Mha worldwide, about 18% of total cultivated land. Agriculture is the largest user of water among human activities: irrigation water withdrawals are 70% of the total anthropogenic use of renewable water resources – about 2630 Gm^3/year (Gm^3/year) out of 3815 Gm^3/year (Table 1). An estimated 50% of agricultural water withdrawals (AWWs) reach the crops – the remainder is lost in irrigation infrastructures (e.g., leaking and/or evaporating from irrigation canals and pipes). Irrigated crops produce about 40% of total agricultural output; their yields are typically twice those of rain-fed crops. For instance, the Food and Agriculture Organization (FAO) estimated that irrigated cereals produce yearly about 60% of a total of 1.2 Gt in the developing countries [3]; globally-averaged irrigated cereal yields for developing countries are thus 3.9 tons/ha, compared with roughly 1.8 tons/ha under rain-fed conditions [3].

In addition to the direct impacts of climate change on crop production [4,5], there is concern about future agricultural water requirements *vis-à-vis* water availability under the combined effects of climate change, growing population demands, and competition from other economic sectors under future socio-economic development. Renewable water resources are being increasingly recognized as essential to the sustainability of human societies in coming decades, just as increasing numbers of people live in water-scarce conditions [6–8].

Table 1
Year 2000 statistics used for calibration in AEZ–BLS

	Cultivated land	Irrig. %	Irrig. land	WRQ	AWW	$\mathrm{Irr}_{\mathrm{eff}}$	TWW	% AW	WRI
WORLD	1540	17.6	271	1350	2630	0.51	3816	69	43,006
MDC	632	10.9	69	255	523	0.49	1215	43	13,999
LDC	908	22.3	202	1095	2106	0.52	2602	81	29,007
NAM	235	10.5	25	107	203	0.53	525	39	5650
WEU	103	17.2	18	53	107	0.50	269	40	2221
PAO	56	9.1	5	16	44	0.37	114	38	1249
EEU+FSU	263	9.8	26	98	197	0.49	344	57	4879
AFR	204	3.8	8	45	91	0.50	101	90	2959
LAM	172	11.5	20	82	187	0.44	265	71	13,413
MEA	75	26.6	20	169	254	0.67	283	90	1072
CPA	146	39.6	58	213	496	0.43	736	67	3622
SAS	200	39.1	78	496	852	0.58	951	90	2547
PAS	70	17.8	12	65	185	0.35	207	89	4107

From first to last column: (1) Cultivated land for the year 2000 (Mha); (2) Shares (%) of irrigated land in total cultivated land for the year 2000; (3) Irrigated land (Mha); (4) Results of AEZ computations of net irrigation water requirements (WRQ, Gm^3 year); (5) FAO AQUASTAT statistics on average 1998–2002 agricultural water withdrawals (AWW, Gm^3 year); (6) Irrigation efficiency ($\mathrm{Irr}_{\mathrm{eff}}$); (7) Total water withdrawals (TWW, Gm^3 year); (8) Agricultural share (%) of water withdrawals; and (9) Renewable internal water resources (WRI, Gm^3 year).

MDC, developed countries; LDC, developing countries; NAM, North America; WEU, Other developed countries (mainly Europe, including Turkey); PAO, Developed Pacific Asia; EEU + FSU, Eastern Europe and former USSR; AFR, Sub-Saharan Africa; LAM, Latin America; MEA, Middle East and North Africa; CPA, East Asia; SAS, South Asia; PAS, Developing countries in Southeast Asia.

With respect to agriculture, considerable research has investigated the impacts of socio-economic development, climate change, and variability on global crop production. Yet a much smaller body of work has investigated implications for irrigation water use, both regionally and globally. On the one hand, most such studies have focused solely on the local and regional aspects of irrigation water demand [9–11]. On the other hand, global analyses to date have largely focused on water availability – for both agriculture and other sectors – using hydrological models to estimate changes in precipitation, evapotranspiration, and river runoff, which are of importance to water resources. Such studies often included some basic interactions of climate and population as a function of the studied socio-economic scenario, to determine levels of regional and global water availability over the 21st century [12–14]. Results indicate that climate change is likely to increase water scarcity around the globe, mostly in regions that already suffer under present conditions, such as the southern Mediterranean, the Middle East, and Sub-Saharan Africa. Within this context, even fewer studies have specifically addressed future regional and global changes in irrigation water for agriculture. Döll and Siebert [15] developed a global irrigation model by integrating simplified agro-ecological and hydrological approaches. Döll [16] used this framework to investigate global impacts of climate change and variability on agricultural water-irrigation demand by comparing the impacts of current and future climate on irrigated cropland. She found that changes in precipitation, combined with increases in evaporative demands, increase the need for irrigation worldwide, with small relative changes in total, about +5–8% by 2070 – depending on the general circulation model (GCM) projection – and larger impacts, about +15%, in Southeast Asia and the Indian subcontinent.

Yet much remains to be done to improve the predictions of future irrigation water requirement in agriculture. First, biophysically and agronomically based hydrology computations, such as those used by Döll [16], should be performed within a spatially detailed agro-ecological zone (AEZ) assessment model, so that water-demand estimates are consistent with predictions of crop biomass production and yield. Second, because many interactive processes determine the dynamics of crop production beyond agro-climatic conditions [4], studies that focus on irrigation water should also include, apart from climate change, the impacts of socio-economic scenarios [3,4,17].

This paper reports on a new methodology aimed to improve, within a coherent AEZ framework, estimates of irrigation water requirements under current and future decades brought about by changes in both climate and socio-economic conditions. As part of this methodology, regional renewable water resources were estimated as a function of precipitation and evapotranspiration. For the analysis, the FAO–International Institute of Applied Systems Analysis (IIASA) agro-ecological modeling framework (AEZ) and associated agro-climatic and land-resources database [18] were employed in conjunction with IIASA's world food system model, or Basic Linked System (BLS) [19,20]. Specifically, we focused on agricultural development within a new A2 socio-economic scenario, A2r, developed at IIASA [21], to quantify global and regional trends from 1990 to 2080, as well as impacts of associated climate change, with and without mitigation options.

Climate change impacts on cultivated land and crop production patterns are described in this Special Issue [5]. In this paper we report on changes in irrigation water demand, focusing on the following research questions:

- What are the implications of mitigating climate change for global and regional irrigation water requirements and withdrawals?
- Where does it matter most?

As a caveat to the reader, both previous literature results and our own computations herein refer mainly to irrigation water requirements (i.e., the amount of water necessary for optimal crop production). Additional considerations on irrigation water efficiency and water costs are necessary to project actual water withdrawals as a function of those requirements, yet the historical data and model feedbacks necessary for such estimates are poorly developed. We nonetheless developed our own rough estimates of changes in irrigation efficiency and water costs over the coming decades, and provide at the end of this paper a first-order quantification of future irrigation water withdrawals and expenditures.

2. Materials and methods

The combination of a spatially detailed biophysical–agronomic assessment tool and a global food system model provided an integrated framework for the assessment of future water resources within this study. Descriptions of the key components of the IIASA modeling systems are given elsewhere [4,5,19]. Here we further specify the methodology employed to compute water-related variables.

2.1. AEZ modeling methodology: crop water requirements

The AEZ model uses detailed agronomic-based procedures to simulate land resources availability and use, farm-level management options, and crop production potentials as a function of climate, soil, and terrain conditions. At the same time, it employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine-grid intervals over the entire globe. It has been validated for use in agricultural resource assessment and applied in many studies, at (sub)national, regional, and global scales [4,18,22]; AEZ is one of the main tools used by the FAO to analyze present and future land resources, both regionally and globally [3].

For this work, AEZ was used to compute water movement through the soil–plant–atmosphere continuum, to assess net crop irrigation water requirements (WRQ). The WRQ is defined herein as the *amount of water – in addition to available soil moisture from precipitation – that crop plants on irrigated land must receive to grow without water stress*. Gross AWWs for irrigation were then estimated from WRQ via an irrigation efficiency parameter ($\mathrm{Irr}_{\mathrm{eff}}$) an indirect proxy of irrigation water loss: $\mathrm{AWW} = \mathrm{WRQ}/\mathrm{Irr}_{\mathrm{eff}}$.

Computations used a gridded climate database of the Climate Research Unit (CRU) of the University of East Anglia, which consists of historical monthly mean data for the period 1901–1996 and includes a monthly mean climatology based on the decades 1961–1990 (mean monthly minimum temperature, mean monthly maximum temperature, precipitation, cloudiness, vapor pressure deficit, wind speed, wet-day frequency). For AEZ applications, the monthly data of CRU were transformed into pseudo-daily data, using spline interpolation for temperature, and by generating rainfall events in accordance with monthly wet-day frequency and rainfall totals in a grid cell.

Computations of WRQ were carried out for each grid cell in five successive steps, in the following manner:

- First, the Global Map of Irrigated Areas was used to define irrigated shares of cultivated land in 5′ latitude × 5′ longitude grid cells (i.e., with a size of about 10 × 10 km at the equator) (http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm).

- Second, based on irrigated shares of cultivated land in each grid cell, agro-ecological suitability for four distinct crop groups in terms of water requirements – wetland rice, a generic dry-land crop, a generic perennial (fruit trees, citrus), and sugar cane – was estimated with AEZ to determine water deficits of crops under rain-fed conditions.
- Third, Crop calendars, from AQUASTAT (http://www.fao.org/ag/agl/aglw/aquastat/water_use/index4.stm) for developing countries and compiled from national statistics for selected developed countries, were used to determine the irrigation-use fraction at each grid cell (i.e., the fraction of time in a year when irrigated crops were actually grown). WRQ was equated to a crop's water deficits, computed in daily time-steps, and summed over the length of each crop growth cycle. Water deficits were derived in AEZ by comparing crop-specific actual and potential evapotranspiration rates [3,18].
- Fourth, total WRQ of each country was computed by determining the contributions of the four simulated crop groups, using agricultural statistics (AQUASTAT online; EUROSTAT online [23]).
- Finally, grid-cell WRQ computations were aggregated to national and regional levels in the world food system model, and up to the world regions considered in the A2r scenario (see below). National-level use fractions of irrigated land, as computed in AEZ and aggregated over grid cells, were harmonized with FAO-reported values (from AQUASTAT) by applying country-specific adjustment factors, to ensure consistency with available water use statistics.

2.2. AEZ modeling methodology: renewable water resources

A robust methodology was developed to assess renewable internal water resources at regional level (WRI), and thus enable the consequences of changes in water requirements and withdrawals to be evaluated under different climate and socio-economic scenarios.

Although current global water resources are sufficient to satisfy irrigation water demands globally, there is concern about specific regions, such as North Africa and the Middle East, the Indian subcontinent, and North China, as to whether future water demand and competition from other sectors may create severe conditions of water scarcity. For this purpose, we defined a *water scarcity index* (WSI) as the ratio of AWWs to internal renewable water resources (WRI), i.e., WSI=AWW/WRI. According to FAO definitions, conditions of water scarcity are impending when water withdrawals exceed 20% of a region's renewable water resources and can be regarded as critical when water withdrawals exceed 40% (http://www.fao.org/ag/agl/aglw/aquastat/water_use/index5.stm).

To estimate WRI from climatology, we ran multiple regressions of observed WRI (data reported in FAO AQUASTAT) against annual precipitation and annual reference evapotranspiration, calculated using average 1961–1990 CRU climatology, and aggregated over individual countries and 35 AEZ–BLS sub-regions (Fig. 1). The regression was estimated in the form $WRI/P=f(P/PET_{ref})$, with f a quadratic function of its argument, had good predictive power ($R^2=0.74$) and plausible parameter values. We then applied this regression to estimating future changes in regional WRI, using levels of precipitation and future reference evapotranspiration according to the climate scenario.

2.3. Socio-economic scenario

This paper focuses on the modified *Special Report on Emissions Scenarios* (SRES) A2r, with lower population projections than the original SRES-A2, and discussed in detail in this Special Issue [21]. Agricultural water resources under A2r were aggregated to ten world regions: North America (NAM),

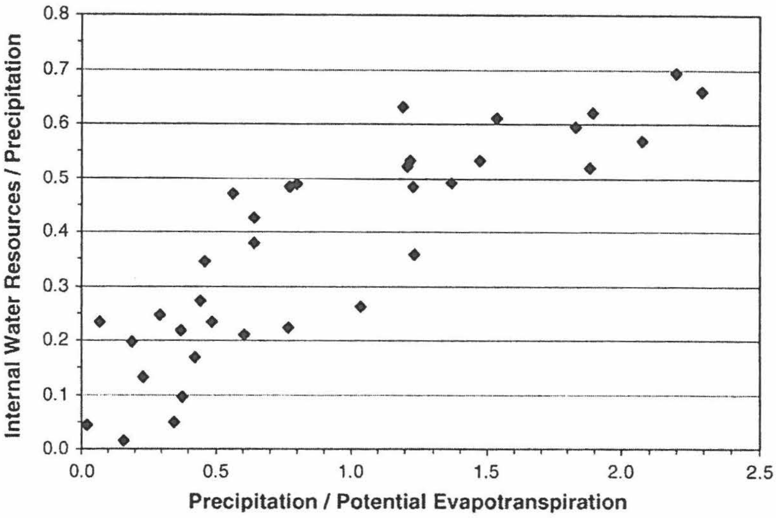


Fig. 1. Scatter diagram to show the ratio of internal renewable water resources to precipitation against ratio of precipitation by reference evapotranspiration. Data are derived from FAO AQUASTAT (for water resources), the CRU 1961–1990 mean climatology (for precipitation), and simulated by AEZ (for potential evapotranspiration).

developed Pacific Asia (PAO), Eastern Europe and former Soviet Union (EEU+FSU), other developed (WEU; mainly Europe, including Turkey), Sub-Saharan Africa (AFR), Latin America (LAM), Middle East and North Africa (MEA), East Asia (CPA), South Asia (SAS), and Southeast Asia (PAS).

Irrigation water requirements in each decade of the A2r reference scenario were computed as follows. First, percentage shares of irrigated land from 1990 to 2080 were specified externally, using data developed by FAO [3]. These data were used to compute total irrigated land extents, $A^i_{\rm irr}(t)$, in Mha, from total cultivated land projected by BLS over the same period. Second, net irrigation water requirements under the reference climate in each decade were estimated using AEZ-derived per hectare water requirements for the reference climate, WRQ(2000), and irrigated land (by 35 BLS regions):

$$\mathrm{WRQ}^i(t) = \mathrm{WRQ}^i(2000)^* A^i_{\rm irr}(t)/A^i_{\rm irr}(2000),$$

where $A^i_{\rm irr}$ is irrigated land in region i.

It is important that the computations of irrigation water requirements discussed herein were dynamically carried out within AEZ, based on biophysical equations of crop water deficits, as previously specified. By contrast, estimates of actual water withdrawals for irrigation were external to the model, and must thus be regarded as first-order approximations: the AEZ–BLS framework currently lacks the economic feedback between land use and water demand variables necessary to compute actual water use realistically. Specifically, regional AWWs were simply estimated from WRQ by assuming a 10% increase in irrigation efficiency from 2000 to 2030 [3], and a further 10% increase from 2030 to 2080, equally in all regions:

$$\mathrm{AWW}^i(t) = \mathrm{WRQ}^i(t)/\mathrm{Irr}^i_{\rm eff}(t),$$

where $\mathrm{Irr}^i_{\rm eff}(t)=\mathrm{Irr}^i_{\rm eff}(2000)*(1+\delta(t))$, and $\mathrm{Irr}^i_{\rm eff}(2000)=\mathrm{WRQ}^i(2000)/\mathrm{AWW}^i(2000)$ is calculated from base-year data. $\mathrm{AWW}^i(2000)$ values were taken from the AQUASTAT online database. With respect to these assumptions, the changes in irrigation water efficiency are highly uncertain, and may importantly depend on regional and international dynamics of water scarcity. Our own assumed increases only represent such interactions implicitly. Furthermore, for the lack of any published projections past 2030, we chose to apply changes to $\mathrm{Irr}(t)$ uniformly across BLS regions, starting from regionally specific values derived from year 2000 statistics. Alternative projections would produce changes in AWW that scale linearly with those presented herein.

Improved estimates in Irr are necessary to improve our projections of water withdrawals. In particular, preliminary calculations we performed indicated that irrigation efficiency correlates well with regional water scarcity, and lead to predicted maximum values of efficiency in the range of 80–90% (data not shown). These values, as discussed in later sections, are consistent with our simple projections of irrigation efficiency in the only two regions undergoing water scarcity by 2100 (i.e., the Middle East and the Indian subcontinent).

Finally, the WSI was computed in each region and through time as:

$$\mathrm{WSI}^i(t) = \mathrm{WRQ}^i(t)/\mathrm{WRI}^i(2000),$$

with $\mathrm{WRI}^i(2000)$ representing renewable internal water resources in region i in the year 2000 from AQUASTAT (http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm). Renewable water resources were assumed constant through time under the A2r reference scenario with no climate change.

The impacts of climate change on agricultural water use over this century were assessed with and without mitigation. The following two-step strategy was followed:

(i) The impacts of socio-economic variables were analyzed against present conditions, without climate change;
(ii) Impacts of climate change, without and with mitigation, were superimposed to this reference scenario, and differences between unmitigated and mitigated climates were computed.

2.4. Climate change scenario generation

GCMs compute future climates under anthropogenic forcing (i.e., present and projected future emissions of greenhouse gases [24]). Their use in studies of climate change impact assessment is widespread [10,25]. We utilized climate change scenarios from two GCMs, HadCM3 and CSIRO (see this Special Issue [5]). Projected GCM climate changes for each decade of interest, from 1990 to 2080, were computed relative to a baseline climate (1961–1990) at 0.5° latitude × 0.5° longitude, and used to generate future agronomic and water data.

Only one socio-economic scenario, A2r, was associated in this work with both non-mitigated and mitigated climates. In other words, the costs of mitigation – and thus potential feedback on the socio-economic path itself – were considered negligible. By contrast, two separate climate change scenarios were considered: SRES A2 climate projections were used as a proxy for the A2r *unmitigated* climate, while SRES B1 climate projections were employed as a proxy for climate change under the A2r *mitigated* scenario. For simplicity, in the following analyses we refer to these two scenarios as A2r and A2r-mit.

The following equations were used to derive water resource variables. Water requirements under climate change for region i and time t, $\mathrm{WRQ}^i_{\mathrm{cc}}(t)$, were computed for each region as the product of average regional aggregated daily water demand – $\mathrm{wrq}^i_{\mathrm{cc}}(t)$, derived from AEZ as a function of changes in temperature and precipitation as well as possible increases in land occupation time (i.e., irrigation land-use fraction) within a year – multiplied by the corresponding amount of irrigated land:

$$\mathrm{WRQ}^{i}_{\mathrm{cc}}(t) = \mathrm{wrq}^{i}_{\mathrm{cc}}(t) * A^{i}_{\mathrm{irr}}(t).$$

For the calculation of water impacts, irrigated land extents were kept the same as in the A2r reference case. However, over those lands, the extent of the growing period was allowed to change in response to climate change. This resulted, in general, in longer growing seasons – and thus increased water demand over and above increases caused by warmer climates – at mid-to-high latitudes, with little changes in the tropics. AWWs under climate change, $\mathrm{AWW}^{i}_{\mathrm{cc}}(t)$, were estimated from net water requirement, similarly to computations in the reference case:

$$\mathrm{AWW}^{i}_{\mathrm{cc}}(t) = \mathrm{WRQ}^{i}_{\mathrm{cc}}(t)/\mathrm{Irr}^{i}_{\mathit{eff}}(t).$$

As in the reference case, irrigation efficiency was assumed to increase by 20% during 2000 to 2080. Subsequently, the WSI was computed by region and time step, as follows:

$$\mathrm{WSI}^{i}_{\mathrm{cc}}(t) = \mathrm{WRQ}^{i}_{\mathrm{cc}}(t)/\mathrm{WRI}^{i}_{\mathrm{cc}}(t),$$

with renewable water resources, $\mathrm{WRI}^{i}_{\mathrm{cc}}(t)$, calculated over time, used to evaluate the estimated regression equation with projected precipitation and potential evapotranspiration, as previously discussed in Section 2.2.

2.5. Economic costs of changes in irrigation water requirements

We used AEZ–BLS computations of water requirements, together with our simple estimates of irrigation efficiency, to derive first-order quantifications of the cost of increasing irrigation under climate change. Water price and irrigation cost data were available for a few regions, and are used herein to estimate the cost of additional irrigation within BLS. For the USA, the cost of providing irrigation to an additional hectare of land was \$290/ha, or \$57/1000 m^3 (derived from available data [23]). This includes the cost of supplying water from different sources, investment in irrigation equipment, facilities, land improvement, and computer technology; maintenance and repair, and labor. Additional capital costs of increasing irrigation on already irrigated land were assumed to be minimal, and included additional pumping and energy cost and/or water price, operation and maintenance, and labor. We estimated these at \$37/1000 m^3 of water withdrawal.

Data available for China suggested average irrigation costs of \$131/ha [26,27]. Given that China applies on average 6000 m^3/ha on irrigated land, the corresponding cost of water was estimated at \$22/1000 m^3. In India, the average cost of groundwater irrigation is \$158/ha, equivalent to \$18/1000 m^3, with 8677 m^3 applied per hectare [28]. In Sub-Saharan Africa, substantially greater prices were related to high water usage (i.e., on average 14,400 m^3/ha [29,30]). Cost estimates for Africa were only made for groundwater pumping, and resulted in \$709/ha, or about \$49/1000 m^3.

We applied these regional unit prices to projected changes in irrigated land and irrigated water amounts in each BLS region. Lacking a dynamic land–water feedback in BLS, as well as any projection on future regional costs, we chose to keep unit costs constant to 2080. Our resulting estimates are thus highly uncertain and are meant to provide only first-order estimates. They may possibly be taken to represent lower limits to future cost, since increased competition for water and energy – and declining subsidies – may lead, in the future, to higher water and energy prices compared to those of today.

2.6. Limitations of modeling framework

Simulation models investigate complex interactions and feedbacks of many variables. As a consequence, several limitations and uncertainties apply to the results presented here. A number of generic limitations, relative to the nature of climate predictions, such as the effects of elevated CO_2 on crop growth and the assumptions on cost of mitigation within A2r, are discussed in this Special Issue [5]. Here we further analyze limitations to estimates of agricultural water resources.

First, under no climate change, we assumed that future increases in water requirements and use would follow proportionally the projected increases in irrigated land. In fact, this assumption is correct only if the average water deficits on current and future additional land are similar. In practice, in some regions irrigation would develop over increasingly marginal land, perhaps with higher annual water requirements than current irrigated areas, so that our computations of WRQ in the reference scenario might underestimate future increases.

Second, the effects of elevated CO_2 were included herein, to simulate a reduction of leaf stomatal resistance and thus transpiration. Crop water-use efficiency – the amount of biomass fixed in photosynthesis to water loss – is believed to increase under elevated CO_2, yet it is unclear whether equations based on leaf-level knowledge are appropriate to capture water dynamics at the field level. The stronger this effect is in real-world field conditions the more it would lower future WRQ. However, it is possible that under climate change the ratio of irrigated to total cultivated land may change in addition to the values already specified in the socio-economic scenario — as an adaptation strategy. By contrast, in these simulations this ratio is the same as in the reference case.

Third, we assumed that irrigation efficiency, or the ratio between WRQ and AWW, although changing through time, would be the same with and without climate change. In fact, it is plausible that — all other things being equal – irrigation efficiency would decrease under climate change, as warmer climates and increased evaporative demands could lead to larger water losses during transportation to the fields. In such cases, future AWW and WSI values would be larger than computed herein.

Fourth, although the WSI is a useful indicator that allows for large-scale regional comparisons, it does not capture water scarcity conditions on a finer scale, such as those that arise from overuse of groundwater resources, a main cause of falling water tables in many key producing world regions. Also, by using annual totals, the WSI does not reveal specific patterns of seasonal water scarcity.

Fifth, the cost estimates for increased irrigation water use discussed here, particularly for Asia and Africa, are only rough estimates. Directly comparable irrigation cost information is not available around the world, so that the average estimates from each country and region involve different cost components. In addition, irrigation water in most countries is often subsidized by governments. For instance, US statistics show that 25% of farms receive off-farm water for free. The costs discussed here are on-farm costs. To estimate direct costs, we assumed that additional water would be supplied by increased irrigation, without the need for a new large water-supply infrastructure. These capital costs for new irrigation projects can be as much as \$15,000/ha in Africa and only \$1500/ha in China [31]. Spread over the lifespan of an irrigation project, about 50 years, these would amount to \$350/ha per year for Africa and \$35/ha per year in China.

Finally, although water amounts computed within the AEZ–BLS systems were consistent with agriculture production figures generated in the A2r development scenario [5], water and crop production were not fully coupled. This is because changes in crop mix and management decisions simulated by BLS were not fully reflected in the AEZ water estimations. Results could be further improved by allowing BLS to allocate irrigated and rain-fed land dynamically, and therefore actual irrigation-water withdrawals, based on cost of water and irrigation infrastructure.

3. Results: world food system, 1990–2080

The following sections describe the results obtained with AEZ–BLS for irrigation water requirements, withdrawals, and renewable water resources. All simulations started in 1990 and were carried out in yearly increments; the results are presented in 10-year time steps, from 2000 to 2080.

3.1. Impacts of socio-economic development, no climate change

We first assessed the implications of the A2r reference scenario on agricultural water use, starting from present conditions (year 2000). Simulation results without climate change represented the reference against which climate change impacts were then analyzed.

3.1.1. Current irrigated area and irrigation water requirements

In the year 2000, world total irrigated area was nearly 18% of total cultivated land, with larger shares in developing countries, especially in Asia (Table 1). These data were combined with BLS-computed global and regional amounts of cultivated land under the A2r reference scenario, to derive amounts of future irrigated areas. BLS estimated total irrigated land of 271 Mha in 2000, of which three-fourths are in developing countries. These figures are in good agreement with current statistics (FAOSTAT; FAO AQUASTAT). By using the methodology previously described, AEZ computed over this land the total net water irrigation requirements of 1350 Gm^3/year (Table 1). Compared to current statistics of water withdrawals for agriculture of 2630 Gm^3/year, the AEZ figures implied an irrigation efficiency ($\mathrm{Irr}_{\mathrm{eff}}$, or the ratio of plant water requirements to water withdrawals) of roughly 50%, also in good agreement with observations. Mirroring the regional distribution and intensity of use of irrigated land, net irrigation requirements in developing countries represent more than three-fourths of the total; they are located mainly in the Indian subcontinent, Southeast Asia, and China. Additionally, by comparing AEZ computations with current statistics of AWWs, irrigation efficiency is quite similar across regions, with values slightly below 40% in those areas with a high percentage of wetland rice cultivation on irrigated land, such as the Asian Pacific and Southeast Asia regions (Table 1).

AEZ–BLS computations of water requirements and agricultural production were combined to estimate crop irrigation water-use efficiency ($\mathrm{WUE}_{\mathrm{irr}}$), defined as the ratio of total net irrigation water requirements to total production. For cereals, production in developing countries amounted to 1.2 Gt in 2000, of which 60% were produced on irrigated land [3]. We thus computed $\mathrm{WUE}_{\mathrm{irr}}$ as about 1015 liters irrigation water per ton of irrigated grain – assuming two-thirds of irrigation water was used for cereal production – a figure quite consistent with observations.

3.1.2. Projected future irrigated area and irrigation water requirements

By 2080, BLS projected global irrigated land of 393 Mha (Table 2), or 22% of global cultivated land. This corresponds to a +45% increase from 2000 levels, or an addition of 122 Mha. Of the additional irrigated land, the large majority – or 112 Mha irrigated – is in developing countries (+56%), mainly in South Asia, Africa, and Latin America. For large Asian producers increases of irrigated land are less

Table 2
BLS-projected irrigated land (Mha) under the A2r scenario, from 2000 to 2080, used for all scenario cases

	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	271	292	313	327	342	356	369	382	393
MDC	69	70	71	73	75	76	77	78	79
LDC	202	222	242	254	268	280	292	304	315
NAM	25	26	28	29	30	30	30	30	31
WEU	18	18	18	18	19	19	19	18	18
PAO	5	5	5	5	5	5	6	6	6
EEU+FSU	26	26	26	27	28	29	29	30	31
AFR	8	10	13	15	18	21	25	29	32
LAM	20	23	28	31	35	38	41	44	46
MEA	20	21	22	23	25	26	27	27	28
CPA	58	62	65	66	67	68	69	70	71
SAS	78	85	92	95	98	101	104	107	109
PAS	12	13	14	15	16	16	17	17	18

pronounced. For instance, in India and China irrigated land by 2080 represents 45% and 50%, respectively, of total cultivated land in these countries, an average increase of 28% compared to the year 2000.

Total net irrigation water requirements, WRQ, increase proportionally with irrigated land (Table 3a). Specifically, global net irrigation requirements increase from 1350 Gm^3/year to 1960 Gm^3/year. Irrigation water requirements increase over 50% in developing regions, and by about 16% in developed regions. The largest relative increases from 2000 to 2080 – also substantial in absolute amounts – were computed for Africa, from 45 to 180 Gm^3/year (+300%) and Latin America, from 82 to 179 Gm^3/year (+119%). Developed regions were computed to add about 40 Gm^3/year in total, with North America (+25 Gm^3/year, or +23%) experiencing the largest increase.

Two main factors are responsible for the increased net irrigation water requirements. Two-thirds of the increases (75–80% in developing countries, but only 50–60% in developed countries) arises from an increase in average daily water requirements caused by warming and changed precipitation patterns, and globally one-third occurs because of extended crop calendars in temperate and sub-tropical zones. Fig. 2 illustrates the variable importance of the two factors in different regions and compares the magnitude of climate change impacts to average net water requirements under reference climate.

3.1.3. Water scarcity

As discussed, the ratio of water withdrawals for irrigation to total internal renewable water resources, or WSI, is an important indicator of regional water status. To derive WSI, AWWs were first estimated in BLS from the net irrigation water requirements (Table 3a and b) by assuming the regional irrigation efficiency would improve, compared to the year 2000, by 10% until 2030 – in agreement with FAO projections [3] – and an additional 10% from 2030 to 2080. For these reasons, estimated relative increases in AWW were much smaller than those computed for WRQ. For instance, global increases in AWW in 2080 were projected to be only +25%, compared to increases of +45% in WRQ.

To produce a more relevant indicator of water scarcity with regard to (irrigated) agriculture, a weighted scheme was used to aggregate WSI for broad world regions using shares of irrigated land in each BLS sub-region in the total regional irrigated land as aggregation weights for AWW and WRI. In the year 2000, small global WSI values of 14% (an aggregate index of 20% for developing countries) were computed, but with

Table 3
BLS projections under A2r reference scenario (without climate change) of (a) net irrigation water requirements (Gm^3); (b) agricultural water withdrawals (Gm^3)

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Net irrigation water requirements (WRQ), Gm^3 water									
WORLD	1350	1453	1559	1630	1707	1773	1840	1903	1961
MDC	255	261	268	274	282	285	289	293	297
LDC	1095	1192	1292	1356	1425	1489	1551	1610	1664
NAM	107	114	121	125	130	130	130	131	132
WEU	53	55	57	57	58	58	59	59	59
PAO	16	16	16	16	17	18	18	19	20
EEU+FSU	98	98	99	102	105	108	111	115	119
AFR	45	57	71	86	103	121	141	162	180
LAM	82	95	112	125	139	150	161	171	179
MEA	169	177	186	195	204	212	218	223	228
CPA	213	227	241	243	247	250	253	257	261
SAS	496	537	576	595	615	633	650	666	681
PAS	65	69	74	78	82	85	87	89	91
(b) Agricultural water withdrawals (AWW), Gm^3 water									
WORLD	2630	2750	2873	2924	3019	3090	3162	3225	3278
MDC	523	517	512	508	512	509	506	505	504
LDC	2106	2233	2361	2416	2507	2582	2656	2720	2775
NAM	203	209	215	216	220	217	214	212	210
WEU	107	106	104	101	100	99	97	95	92
PAO	44	41	39	38	38	39	40	40	41
EEU+FSU	197	193	188	188	190	192	194	197	201
AFR	91	113	137	161	189	218	253	287	317
LAM	187	215	248	271	297	318	337	351	364
MEA	254	258	262	267	275	281	284	287	288
CPA	496	510	524	514	514	514	513	513	513
SAS	852	900	943	951	971	986	999	1010	1019
PAS	185	191	198	202	208	212	214	216	216

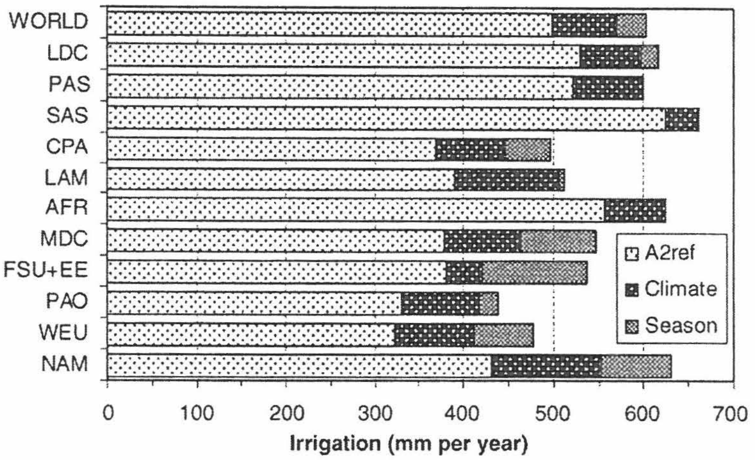
Note: The changes in WRQ mirror the increases in irrigated land, whereas increases in AWW are smaller, because it is assumed that irrigation water efficiency will increase from year 2000 values in Table 1 by 20% by 2080.

large regional variation. Specifically, WSI for the North Africa and Middle East region was 61% and for South Asia (Indian sub-continent) it was 43% (Table 4), in good agreement with water scarcity reported in FAO data [3]. According to FAO, critical regional water status is attained whenever WSI>40%. Under the A2r reference scenario, BLS computed that such critical levels would continue in both MEA and SAS regions, with water scarcity likely to worsen in the South Asia region. However, overall the global weighted index changes little – for several regions the weighted regional WSI even decreases over time – as assumed improvements in irrigation efficiency effectively mitigate the growth in net irrigation requirements.

3.2. Impacts of socio-economic development, with climate change

Impacts of climate change on net irrigation water requirements, AWWs, and renewable water resources were analyzed using two GCMs, those of Hadley (HADCM3) and the Commonwealth Scientific and

(a) Hadley



(b) CSIRO

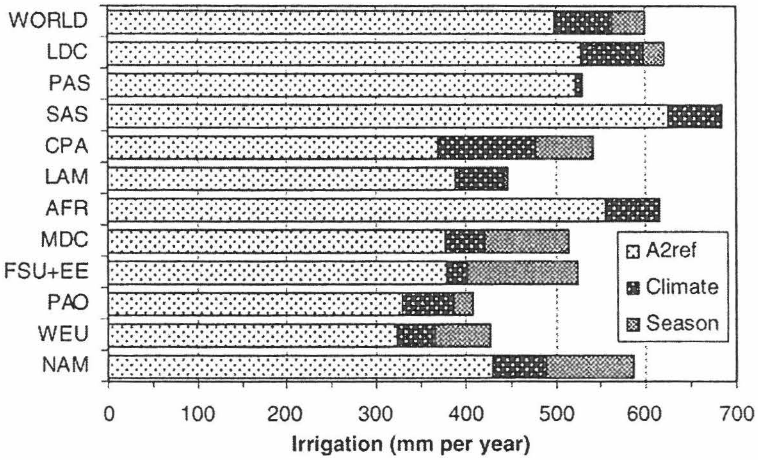


Fig. 2. Impacts of A2r climate change on average regional net irrigation water requirements (mm per year) in 2080, for (a) Hadley GCM and (b) CSIRO GCM. Diagrams indicate values under reference climate (A2r-ref), increase because of warming and changed precipitation patterns (Climate), and increases caused by expanded crop calendars (Season).

Industrial Research Organisation CSIRO [5]. AEZ–BLS simulations were performed with and without mitigation, and the results were tabulated in 10-year time steps. In general, in these simulations the higher temperatures and altered precipitation regimes impacted net irrigation water requirements in two distinct ways. First, by affecting crop evapotranspiration rates, and thus crop water demand; and second, by altering crop calendars (i.e., by modifying – typically extending in temperate and sub-tropical zones – the duration over which a crop could be grown and irrigated at a given location).

3.2.1. Irrigation water requirements

Impacts of climate change *on world aggregate* net irrigation water requirements are significant. Total increases of about 395–410 Gm^3 water in 2080 were projected with AEZ–BLS, similarly under both

Table 4
BLS projections of weighted regional water scarcity index (WSI, %) for the A2r reference scenario

	2000	2010	2020	2030	2040	2050	2060	2070	2080
WORLD	13.6	14.3	14.9	14.6	14.5	14.4	14.3	14.2	14.2
MDC	5.0	5.0	5.0	5.0	5.1	5.0	5.0	4.9	4.9
LDC	19.6	20.2	20.7	20.1	19.8	19.5	19.3	19.1	18.9
NAM	6.9	7.0	7.2	7.2	7.3	7.1	6.9	6.8	6.6
WEU	4.6	4.7	4.8	4.8	4.8	4.9	4.9	5.0	5.0
PAO	4.6	4.1	3.8	3.7	3.8	3.8	3.9	4.0	4.0
EEU+FSU	4.0	3.9	3.9	3.9	3.9	3.9	4.0	4.0	4.1
AFR	2.8	3.3	3.9	4.6	5.3	6.2	7.1	8.0	8.8
LAM	1.6	1.8	2.1	2.3	2.4	2.6	2.7	2.8	2.9
MEA	60.9	60.4	60.1	60.3	61.2	61.4	61.0	60.8	60.7
CPA	15.0	15.5	15.9	15.5	15.3	15.1	14.9	14.8	14.6
SAS	43.2	45.6	47.7	47.5	47.7	47.9	48.1	48.2	48.3
PAS	5.2	5.5	5.8	5.9	6.1	6.3	6.4	6.5	6.7

Note: To better reflect water scarcity with regard to agricultural water demand, a weighted index has been calculated using the share of each BLS sub-region's irrigated land in the regional total irrigated land as weights in aggregation.

GCM scenarios (Table 5), i.e., a +20% increase over the net water requirements of 1960 Gm^3 water as computed for the A2r reference case. Additional simulations showed that about 65% of such increases are from higher crop water demands under the changed climate, while the remainder, or 35%, result from extended crop calendars. Importantly, unlike for agricultural production, for which the impacts of socio-economic scenarios are much more important than those of climate change in determining absolute values in 2080 [5,19]), in the case of WRQ the increases computed for 2080 are quite comparable, namely 400 Gm^3 additional net irrigation water requirements from climate change and 600 Gm^3 water from socio-economic development.

Some important regional dynamics were also computed, with similar results among GCMs. First, in 2080, net irrigation requirements from climate change increase, in relative terms, significantly more in developed (+45% under Hadley, +36% under CSIRO) than in developing regions (+17% under Hadley, +17% under CSIRO). Increases in net irrigation requirements are uniformly high in developed countries. In developing regions, largest increases were computed in East Asia (+35% under Hadley, +47% under CSIRO) because of a concurrence of both increased water requirements per hectare and extending crop calendars.

The time evolution of net water requirements computed by BLS indicates a smooth transition (i.e., it followed the year 2000 regional patterns with gradual increases in each decade). Exceptions are the Indian subcontinent (in Hadley) and the Southeast Asian region (in CSIRO), for which BLS computed small decreases in net irrigation water requirements up to 2040. These dynamics can be explained by two interacting factors: First, low levels of warming earlier in the century, combined with increased precipitation signals, may improve crop water balances before 2050. After 2050, temperature increases are likely strong enough to increase water deficits – and thus irrigation requirements of crops – regardless of changes in precipitation patterns. Second, before 2050 CO_2 concentrations may contribute to lower crop water demands over and above increases caused by warmer temperatures; after 2050, the temperature signal would overcome these positive CO_2 effects.

Table 5
Changes in projected net irrigation water requirements (Gm^3) under scenario A2r (without mitigation) compared with the A2r reference scenario (no climate change), for Hadley and CSIRO climates

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Hadley climate change									
WORLD	0	36	76	113	154	196	264	335	409
MDC	0	15	32	45	59	73	93	113	133
LDC	0	21	45	68	95	124	171	222	276
NAM	0	1	2	3	4	5	6	7	8
WEU	0	10	20	30	39	48	60	72	84
PAO	0	6	11	15	20	25	32	41	49
EEU+FSU	0	13	27	40	54	68	92	117	143
AFR	0	8	18	28	41	55	79	105	132
LAM	0	1	2	3	4	5	6	7	8
MEA	0	7	14	22	29	37	45	53	61
CPA	0	4	7	10	12	15	19	24	28
SAS	0	1	1	2	2	3	4	5	7
PAS	0	6	11	15	20	25	32	41	49
(b) CSIRO climate change									
WORLD	0	42	89	125	164	203	264	328	395
MDC	0	12	25	33	42	50	68	87	107
LDC	0	30	64	92	122	153	196	241	288
NAM	0	7	15	18	22	25	33	40	48
WEU	0	2	3	5	8	10	13	16	19
PAO	0	0	0	1	1	1	2	4	5
EEU+FSU	0	4	8	12	15	18	27	36	46
AFR	0	1	2	3	4	6	10	14	19
LAM	0	2	5	8	11	14	18	22	27
MEA	0	3	6	10	14	19	25	32	39
CPA	0	18	38	49	60	71	88	105	122
SAS	0	6	12	20	29	38	47	56	65
PAS	0	0	−1	−1	0	0	1	1	1

3.2.2. *Mitigation*

Under the A2r-mit scenario, BLS computed, under both GCMs, smaller increases in net irrigation requirements in 2080, compared with no mitigation (Tables 6 and 7). Specifically, changes in WRQ were projected to be in the range of 220–275 Gm^3 water, or +13% to +14% compared with the reference (no climate change) case. Regional trends were similar to those discussed for the unmitigated case, in terms of both direction and magnitude of asymmetries between developed and developing regions. For each region, the magnitude of climate impacts was projected to be smaller than under A2r, but with roughly the same groups of winners and losers as indicated previously. We computed the absolute differences between irrigation water demands under A2r-mit and A2r, for both GCMs.

Mitigation reduces by roughly 30–40% the *additional* net irrigation water requirements in 2080 of the unmitigated A2r scenario, quite similarly across developed and developing regions, with somewhat more pronounced decreases under the Hadley climate. Additional to the differences discussed so far, climate mitigation created its own set of winners and losers (i.e., regions that become, in given decades,

Table 6
Changes in net irrigation water requirements (Gm^3) under the A2r-mit scenario (with mitigation) compared with the A2r reference scenario (no climate change), for Hadley and CSIRO climates

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Hadley									
WORLD	0	27	58	86	117	148	181	215	251
MDC	0	16	33	45	57	69	74	78	82
LDC	0	11	25	41	59	78	107	137	169
NAM	0	8	17	23	29	35	36	37	39
WEU	0	3	6	9	11	14	15	16	17
PAO	0	0	1	1	2	2	3	3	4
EEU+FSU	0	6	12	15	19	23	25	27	29
AFR	0	1	2	4	6	8	10	13	16
LAM	0	3	6	10	15	19	25	31	37
MEA	0	2	5	8	12	17	18	20	22
CPA	0	2	5	15	25	35	42	50	57
SAS	0	−1	−2	−7	−12	−17	−6	6	18
PAS	0	2	5	6	8	9	9	9	9
(b) CSIRO									
WORLD	0	58	124	143	164	184	212	240	269
MDC	0	15	32	38	44	51	57	63	70
LDC	0	43	92	105	119	133	155	177	199
NAM	0	6	13	17	22	26	28	30	33
WEU	0	3	6	7	8	9	10	11	12
PAO	0	0	0	1	1	2	2	3	3
EEU+FSU	0	7	15	16	17	19	22	25	29
AFR	0	1	2	3	4	6	8	11	14
LAM	0	2	5	7	9	11	13	15	17
MEA	0	5	11	14	17	20	23	26	30
CPA	0	19	41	47	54	60	70	79	89
SAS	0	14	30	30	30	30	34	38	41
PAS	0	0	−1	0	1	1	1	1	0

either better or worse off with mitigation, compared with the unmitigated climate change scenario results). Specifically, under both GCMs, BLS computed a small *increase* in aggregate net irrigation requirements in developed countries under mitigation, compared with no mitigation, up to 2040. Individually, negative effects of mitigation (i.e., increases of water requirements compared with non-mitigated results) occur in both some developed and developing regions, by up to 2.5% under Hadley and by up to 6.5% under CSIRO. Such results are related to some differences in temperature and precipitation signals between the A2r and A2r-mit climate scenarios, as well as to differences in CO_2 concentrations and their respective effect on potential evapotranspiration and subsequent water balance calculations.

Mitigation becomes beneficial in all regions in the second half of the century only. Maximum benefits were computed for 2080, with a reduction in estimated regional AWWs of up to −14.5% under Hadley and up to −10.5% under CSIRO. In relative terms, reductions of water withdrawals through climate mitigation in 2080 are about twice as large in developed countries as in developing regions.

Table 7
Effects of climate mitigation on irrigation water demand

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Hadley climate change									
WORLD	0.0	−0.8	−1.6	−1.8	−2.2	−2.5	−4.1	−5.5	−6.9
MDC	0.0	0.0	0.1	−0.2	−0.6	−0.9	−5.1	−8.9	−12.3
LDC	0.0	−1.1	−1.9	−2.2	−2.5	−2.9	−3.9	−4.8	−5.7
NAM	0.0	1.1	2.0	0.8	−0.2	−1.2	−4.9	−8.4	−11.5
WEU	0.0	−2.1	−3.9	−2.4	−1.1	0.1	−5.6	−10.4	−14.6
PAO	0.0	−0.9	−1.7	−1.6	−1.4	−1.1	−5.3	−8.8	−11.8
EEU+FSU	0.0	0.2	0.4	−0.1	−0.6	−1.1	−5.1	−8.7	−12.0
AFR	0.0	0.9	1.9	1.6	1.3	1.0	−0.5	−1.9	−3.4
LAM	0.0	−0.3	−0.3	−1.2	−2.3	−3.4	−5.1	−6.7	−8.1
MEA	0.0	−0.4	−0.7	−0.3	0.1	0.5	−1.6	−3.5	−5.4
CPA	0.0	−6.6	−12.2	−10.1	−8.1	−6.2	−7.2	−8.1	−9.0
SAS	0.0	1.2	2.5	0.5	−1.5	−3.3	−3.2	−3.2	−3.1
PAS	0.0	1.0	2.1	1.1	0.3	−0.5	−2.0	−3.3	−4.6
(b) CSIRO climate change									
WORLD	0.0	1.1	2.0	1.0	0.0	−0.9	−2.6	−4.1	−5.6
MDC	0.0	1.4	2.6	1.6	0.8	0.0	−3.5	−6.7	−9.5
LDC	0.0	1.0	1.9	0.8	−0.2	−1.1	−2.4	−3.6	−4.7
NAM	0.0	−0.6	−1.2	−0.7	−0.2	0.3	−2.9	−5.8	−8.5
WEU	0.0	3.3	6.4	3.2	0.3	−2.3	−5.2	−7.9	−10.3
PAO	0.0	−0.4	−0.8	0.3	1.4	2.6	−1.9	−5.8	−9.2
EEU+FSU	0.0	3.2	6.1	4.1	2.2	0.3	−3.6	−7.0	−10.1
AFR	0.0	−0.1	−0.2	−0.2	−0.2	−0.3	−1.3	−2.3	−3.2
LAM	0.0	0.1	0.2	−0.4	−1.1	−1.8	−3.0	−4.2	−5.3
MEA	0.0	1.4	2.8	2.0	1.3	0.6	−0.9	−2.3	−3.6
CPA	0.0	0.6	1.2	−0.5	−1.9	−3.2	−5.2	−6.9	−8.6
SAS	0.0	1.6	3.1	1.8	0.5	−0.8	−1.6	−2.5	−3.3
PAS	0.0	−0.1	−0.3	0.2	0.8	1.3	0.6	−0.1	−0.9

Percentage changes in agricultural water withdrawals between scenarios A2r-mit and A2r, Hadley and CSIRO climate.

3.2.3. Renewable water resources and security under climate change

We estimated changes in renewable fresh water resources as a function of changes in precipitation and potential evapotranspiration, based on a cross-country regression established under current climate conditions. Table 8 shows results for 2080, with global renewable water resources being reduced by −10% under Hadley, but slightly increased (+2%) under CSIRO, compared with the reference scenario. In particular, under the Hadley climate, significant reductions were computed for Europe (−19%), the Middle East (−20%), and most pronounced for Latin America (−42%), where rainfall volume under the A2r climate change decreases by −20%. At the same time, internal renewable water resources under Hadley increase in some regions, for instance in China (+14%) and the Indian subcontinent (+25%). These regional patterns of change are maintained under the CSIRO climate change, although the magnitudes of the projected changes are smaller and with fewer extremes – the largest deviation occurs for the Middle East region (−15%).

Table 8
Projected changes in renewable internal water resources (WRI) under climate change scenarios A2r and A2r-mit in 2080 compared with the A2r reference scenario (no climate change)

	Hadley		CSIRO	
	A2r	A2r-mit	A2r	A2r-mit
WORLD	−10.8	−6.0	1.5	2.0
MDC	−2.3	−0.1	0.0	0.9
LDC	−14.8	−8.8	2.2	2.5
NAM	−3.9	1.0	−4.2	−1.9
WEU	−19.4	−13.0	−5.2	−1.8
PAO	−1.7	−4.4	−2.8	−2.2
EEU+FSU	7.1	5.7	7.8	6.2
AFR	−3.6	−3.9	−7.2	−3.4
LAM	−41.9	−28.2	−2.8	0.0
MEA	−20.3	−13.3	−14.6	−9.5
CPA	13.8	13.6	4.9	3.2
SAS	24.8	22.8	18.7	13.2
PAS	5.3	6.7	15.7	10.2

The combined impacts of climate change on both irrigation water requirements and the availability of internal renewable water resources were captured by computing the weighted regional WSI under projected climates, both for Hadley and CSIRO, for non-mitigated and mitigated conditions. In both cases of non-mitigated climate change, the global WSI changes from 14% in the A2r reference scenario in the year 2080 to 17% (Table 9 for Hadley and Table 10 for CSIRO), and for the developing countries from 19% (A2r reference in year 2080) to 22%. Changes of the WSI appear especially dramatic under non-mitigated climate change for the MEA region, where the A2r reference value of 61% increases toward 90% and above. A large increase of WSI also occurs in East Asia, from a 2080 value of 15% in the A2r reference to 22% under the Hadley climate. However, non-mitigated climate change improved the WSI of 2080 in South Asia, compared with the value computed in the A2r reference scenario, caused by large precipitation increases (about +15%) in both Hadley and CSIRO projections.

Mitigation produced a clear improvement in water scarcity conditions in nearly all regions and scenarios (the exception being the SAS region because of the peculiarities in changing rainfall).

3.2.4. *Economic costs of increased irrigation water requirements*

To quantify broadly the direct costs of the impacts of climate change on irrigation, cost estimates in the range 0.03–0.05 US\$/m^3, previously discussed, were applied to computed changes in water withdrawals relative to the A2r reference scenario. In accordance with available survey data, a unit cost of 40 US\$/km^3 for increasing irrigation water use in existing irrigated land was used for developed countries and Latin America. A lower rate of 30 US\$/km^3 was applied for Asian regions, and somewhat higher costs −50 US \$/km^3 – were used for irrigated land in the mostly semi-arid or arid countries of Africa and Middle East. In this way, global *annual* costs by 2080 of additional irrigation water withdrawals caused by climate change were estimated at 24–27 billion US\$ (Fig. 3a). Depending on climate scenario, the additional annual cost for developed countries amounted to 8–10 billion US\$, and for developing countries the range was 16–17 billion US\$ annually. Comparing the results of (mitigated) scenario A2r-mit with the outcomes

Table 9
Projections of weighted regional water scarcity index (WSI) under climate change impacts on both net crop water requirements and renewable water resources

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Projected WSI under non-mitigated A2r scenario (using Hadley A2 climate change)									
WORLD	13.6	14.8	16.0	15.9	16.0	16.2	16.5	16.8	17.1
MDC	5.0	5.3	5.6	5.9	6.2	6.4	6.6	6.9	7.1
LDC	19.6	20.9	22.2	21.7	21.6	21.5	21.7	22.0	22.4
NAM	6.9	7.5	8.2	8.7	9.3	9.6	10.0	10.3	10.7
WEU	4.6	5.2	5.9	6.3	6.8	7.3	8.2	9.1	10.1
PAO	4.6	4.3	4.3	4.3	4.4	4.6	5.0	5.5	5.9
EEU+FSU	4.0	4.1	4.2	4.4	4.5	4.7	4.9	5.2	5.4
AFR	2.8	3.3	3.9	4.7	5.6	6.6	7.9	9.1	10.4
LAM	1.6	2.0	2.6	3.0	3.6	4.1	4.8	5.6	6.6
MEA	60.9	61.5	62.4	64.6	67.8	70.3	75.4	81.3	88.1
CPA	15.0	17.1	19.3	18.4	17.8	17.3	17.3	17.3	17.4
SAS	43.2	43.4	43.3	43.3	43.7	44.0	43.3	42.7	42.0
PAS	5.2	5.5	5.9	6.3	6.7	7.1	7.2	7.2	7.2
(b) Projected WSI under mitigated A2r-mit scenario (using Hadley B1 climate change)									
WORLD	13.6	14.4	15.1	14.9	14.9	14.9	15.1	15.3	15.5
MDC	5.0	5.3	5.7	5.9	6.2	6.3	6.3	6.2	6.2
LDC	19.6	20.0	20.4	19.8	19.5	19.2	19.5	19.9	20.3
NAM	6.9	7.6	8.5	8.8	9.3	9.5	9.3	9.1	9.0
WEU	4.6	5.1	5.6	6.1	6.7	7.4	7.6	7.8	8.0
PAO	4.6	4.3	4.2	4.3	4.4	4.6	4.9	5.1	5.4
EEU+FSU	4.0	4.2	4.3	4.4	4.5	4.7	4.7	4.8	4.9
AFR	2.8	3.4	4.1	4.9	5.8	6.8	7.9	9.0	9.9
LAM	1.6	2.0	2.5	2.9	3.3	3.7	4.1	4.5	5.0
MEA	60.9	62.2	63.8	68.5	74.5	80.1	78.6	77.4	76.5
CPA	15.0	15.3	15.6	15.6	15.7	15.9	15.8	15.7	15.6
SAS	43.2	43.2	42.9	40.3	38.4	36.6	37.8	39.0	40.1
PAS	5.2	5.6	6.1	6.3	6.5	6.6	6.7	6.8	6.8

Note: To better reflect water scarcity with regard to agricultural water demand, a weighted index has been calculated using the share of each BLS sub-region's irrigated land in the regional total irrigated land as weights in aggregation.

of (non-mitigated) scenario A2r, the benefits of climate mitigation were estimated at 8–10 billion US$ annually (Fig. 3b), quite uniformly spread over developed (3–4 billion US$) and developing countries (5–6 billion US$).

4. Discussion

Our results indicate that both socio-economic development and climate change may significantly impact global and regional net irrigation requirements, and thus AWWs. Against the current amount of about 1350 Gm^3 net water requirements, BLS computed by 2080 a 45% increase, to over 1960 Gm^3 water worldwide. However, because irrigation efficiency was also assumed to increase by 20% until 2080, these dynamics in net crop water requirements correspond to smaller increases of AWWs – globally +25% by

Table 10
Projections of weighted regional water scarcity index (WSI) under climate change impacts on both net crop water requirements and renewable water resources

	2000	2010	2020	2030	2040	2050	2060	2070	2080
(a) Projected WSI under non-mitigated A2r scenario (using CSIRO A2 climate change)									
WORLD	13.6	14.9	16.1	16.1	16.2	16.4	16.5	16.7	16.8
MDC	5.0	5.3	5.6	5.7	5.8	5.9	6.1	6.4	6.7
LDC	19.6	21.0	22.2	22.1	22.1	22.2	22.0	21.9	21.8
NAM	6.9	7.6	8.5	8.7	9.0	9.0	9.4	9.8	10.1
WEU	4.6	4.9	5.1	5.3	5.7	6.0	6.4	6.9	7.3
PAO	4.6	4.2	3.9	3.9	4.0	4.1	4.5	4.9	5.3
EEU+FSU	4.0	4.1	4.1	4.2	4.3	4.4	4.6	5.0	5.3
AFR	2.8	3.4	4.0	4.7	5.6	6.5	7.7	9.0	10.3
LAM	1.6	1.9	2.2	2.4	2.7	2.8	3.1	3.3	3.5
MEA	60.9	61.1	61.5	65.9	71.4	76.6	82.2	88.6	96.1
CPA	15.0	16.8	18.6	18.9	19.4	19.8	20.5	21.0	21.6
SAS	43.2	45.8	48.3	48.8	49.8	50.8	47.4	44.5	42.0
PAS	5.2	5.3	5.5	5.5	5.7	5.8	5.8	5.8	5.9
(b) Projected WSI under mitigated A2r-mit scenario (using CSIRO B1 climate change)									
WORLD	13.6	14.9	16.2	15.9	15.8	15.6	15.7	15.9	16.0
MDC	5.0	5.3	5.6	5.7	5.9	5.9	5.9	6.0	6.0
LDC	19.6	21.1	22.4	21.7	21.2	20.8	20.8	20.9	21.0
NAM	6.9	7.4	8.0	8.3	8.8	8.9	8.9	8.8	8.8
WEU	4.6	5.1	5.7	5.6	5.8	5.8	6.0	6.1	6.3
PAO	4.6	4.1	3.8	4.0	4.2	4.6	4.7	4.8	4.9
EEU+FSU	4.0	4.2	4.4	4.4	4.4	4.4	4.5	4.7	4.8
AFR	2.8	3.3	3.9	4.7	5.6	6.5	7.6	8.7	9.7
LAM	1.6	1.9	2.2	2.4	2.6	2.8	2.9	3.0	3.2
MEA	60.9	66.4	72.7	74.7	77.6	79.7	81.0	82.7	84.7
CPA	15.0	16.9	18.9	18.7	18.7	18.7	19.1	19.5	19.9
SAS	43.2	45.4	47.4	45.8	44.7	43.6	43.8	44.0	44.1
PAS	5.2	5.2	5.3	5.5	5.7	5.9	6.0	6.0	6.1

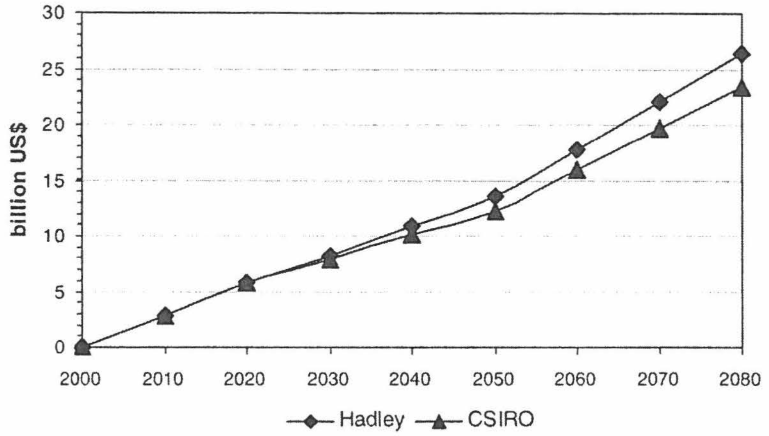
Note: To better reflect water scarcity with regard to agricultural water demand, a weighted index has been calculated using the share of each BLS sub-region's irrigated land in the regional total irrigated land as weights in aggregation.

2080 – from about 2630 Gm^3 water in 2000 to about 3280 Gm^3 in 2080. These estimates represent a response to the rise in irrigated land projected over this century.

The context behind these figures is that land and water resources, together with technological progress, appear to be sufficient to sustain irrigated production globally within the A2r socio-economic development and associated climate change, although with specific regional problems. Importantly, this study quantified the potential benefits of mitigation to the agricultural water sector as a whole. Results can be summarized as follows (ranges indicate GCM differences):

1) Under the socio-economic development pathways of the A2r reference scenario, without climate change, agricultural water requirements are projected to increase by about 45%. Accordingly, water withdrawals increase 25%, from 2630 Gm^3 in 2000 to 3280 Gm^3 in 2080. These figures are based on an expansion of irrigated areas by 122 Mha (i.e. +45%) and an increase in irrigation efficiency by

(a) Global impact of climate change on cost of agricultural water withdrawals



(b) Global effect of mitigation on cost of agricultural water withdrawals

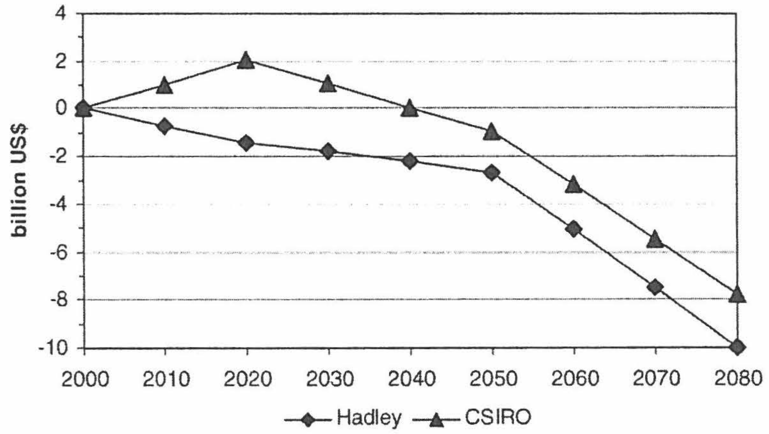


Fig. 3. Impacts of climate change and effects of mitigation on agricultural water withdrawals. Positive values indicate additional annual costs, negative values correspond to *benefits* of mitigation (i.e., reduced irrigation costs with respect to the unmitigated case). (a) Global impact of climate change and (b) net global effect of mitigation, defined as A2r-mit minus A2r values.

20%. While AWW is projected to modestly decrease in developed countries (20 Gm^3 or −4%), it increases in developing countries by 540 Gm^3 (i.e., +32%).

2) Impacts of climate change on irrigation water requirements by 2080 are an additional 395–410 Gm^3 water in terms of net water requirements, which corresponds to an additional 670–725 Gm^3 in AWWs, compared with total agricultural withdrawals of 3280 Gm^3 in the reference case (without climate change). These figures mean an increase of about +20% in global irrigation water needs in 2080. Two-thirds of the increase (75–80% in developing countries, but only 50–60% in developed countries) results from an increase in daily water requirements, and one-third occurs because of extended crop calendars in temperate and sub-tropical zones.

3) In terms of net water requirements, global water requirements in 2080, under climate change and with mitigation, are 125–160 Gm^3 less than without mitigation. This projection corresponded to savings of 220–275 Gm^3 in AWWs. These figures represent only 5–7% of the global irrigation water needs under the non-mitigated A2r climate in 2080, yet in relative terms they mean a reduction of about 40% in additional water requirements from climate change. The distribution of these effects is rather homogeneous across developed and developing regions.
4) By 2080, the global *annual* costs of additional irrigation water withdrawals for existing irrigated land caused by climate change are estimated at 24–27 billion US$. Benefits of climate mitigation are small or even negative up to around 2040, but amount to some 8–10 billion US$ annually by 2080.
5) The time evolution of irrigation water requirement was not constrained by the 2080 end results. For instance, aggregated water requirements in developed regions up to 2030 *increased* under mitigation with respect to no mitigation. Individually, negative effects of mitigation (i.e., increases in water requirements compared to non-mitigated results) occur both in some developed and in some developing regions, by up to 2.5% under Hadley and by up to 6.5% under CSIRO. Mitigation becomes beneficial in all regions only in the second half of the century. Maximum benefits were computed for 2080, with a reduction in estimated regional AWWs of up to −14.5% under Hadley and up to −10.5% under CSIRO.
6) The weighted WSI used to measure regional water scarcity in relation to agricultural water demand indicates that non-mitigated climate change could seriously affect the already water-critical Middle East region and may also aggravate scarcities in the Indian subcontinent. Even for South Asia, where WSI improved with climate change through an increased monsoon precipitation, seasonal water scarcity may intensify.

5. Conclusions

In summary, our simulation results suggest the following. *First*, globally the impacts of climate change on increasing irrigation water requirements could be nearly as large as the changes projected from socio-economic development in this century. *Second*, the effects of mitigation on irrigation water requirements can be significant in the coming decades, with large overall water savings, both globally and regionally. *Third*, however, some regions may be negatively affected by mitigation actions (i.e., become worse-off than under non-mitigated climate change) in the early decades, depending on specific combinations of CO_2 changes that affect crop water requirements and GCM-predicted precipitation and temperature changes. Overall, this early ‘counter’ effect was less significant for water resources than the simulated transient CO_2 effects in the case of crop yields and agricultural production [5].

As discussed, our projections of actual water withdrawals and associated costs are only rough estimates that represent a first attempt at quantification of these important variables. Future studies need to include dynamic interactions of land and water costs regionally and globally to provide more realistic projections of both irrigation water efficiency and cost as a function of water scarcity; they should also include competition from other sectors.

Finally, our analysis indicates that mitigation can and should play an important role in reducing the impacts of climate change on agricultural water resources, globally and regionally. Countries that implement regional and global mitigation actions should also create additional resources to help those regions where the intended benefits do not materialize by enabling a range of adaptation options – particularly in those developing countries where food security is fragile and water resources are already vulnerable today.

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Appendix A. Table of abbreviations

AEZ	Agro-ecological zones
AFR	Africa
A_{irr}	Total irrigated land extent
AWW	Gross agricultural water withdrawals for irrigation
BLS	Basic Linked System (world food system/economic model)
CPA	East Asia
CRU	Climate Research Unit of the University of East Anglia
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EEU	Eastern Europe
FAO	Food and Agriculture Organization of the United Nations
FSU	Former Soviet Union
GCM	General Circulation Model
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
$\mathrm{Irr}_{\mathrm{eff}}$	Irrigation efficiency
LAM	Latin America
MEA	Middle East and North Africa
NAM	North America
P	Precipitation
PAO	Pacific Asia
PAS	Southeast Asia
$\mathrm{PET}_{\mathrm{ref}}$	Reference evapotranspiration
SAS	South Asia
SRES	Special Report on Emissions Scenarios
UN	United Nations
USDA	United States Department of Agriculture
WEU	Other developed, mainly Europe, including Turkey
WMO	World Meteorological Organization
WRI	Internal renewable water resources
WRQ	Net crop irrigation water requirements
WSI	Water scarcity index
$\mathrm{WUE}_{\mathrm{irr}}$	Crop irrigation water use efficiency

References

[1] F.N. Tubiello, Climate Variability and Agriculture: Perspectives on Current and Future Challenges. In: B. Knight (Ed.), Impact of Climate Change, Variability and Weather Fluctuations on Crops and Their Produce Markets. Impact Reports, Cambridge, UK, 2005, pp. 47–66.

[2] J. Diamond, Guns, Germs, and Steel: The Fates of Human Societies, Norton, New York, 1997.

[3] J. Bruinsma (Ed.), World Agriculture: Towards 2015/1030, A FAO Perspective, Food and Agricultural Organization of the United Nations, Rome, 2003, 432 pp.

[4] G. Fischer, M. Shah, F.N. Tubiello, H. van Velthuizen, Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080, Philos. Trans. R. Soc. B 360 (1463) (2005) 2067–2083, doi:10.1098/rstb.2005.1744.

[5] F.N. Tubiello, G. Fischer, Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080, Technol. Forecast. Soc. Change 74 (2007) 1030–1056, doi:10.1016/j.techfore.2006.05.027.

[6] Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis, Island Press, Washington DC, 2005.

[7] R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J. Dokken, IPCC special reports, Land Use, Land-Use Change, and Forestry, Cambridge University Press, Cambridge, 2000, 324 pp.

[8] Stockholm Environment Institute, UN Comprehensive Assessment of the Freshwater Resources of the World, 1997, Stockholm Environment Institute/World Meteorological Organization, Stockholm, 1997.

[9] C.R. Izaurralde, N.J Rosenberg, R.A. Brown, A.M. Thomson, Integrated Assessment of Hadley Center (HadCM2) Climate-Change Impacts on Agricultural Productivity and Irrigation Water Supply in the Conterminous United States: Part II. Regional Agricultural Production in 2030 and 2095, Agricultural and Forest Meteorology, vol. 117, 2003, pp. 97–122.

[10] J. Reilly, F.N. Tubiello, B. McCarl, J. Melillo, Climate change and agriculture in the United States, in: J. Melillo, G. Janetos, T. Karl (Eds.), Climate Change Impacts on the United States: Foundation, USGCRP, Cambridge University Press, Cambridge, 2001, 612 pp.

[11] D.N. Yates, K.M. Strzepek, Modeling economy-wide climate change impacts on Egypt: a case for an integrated approach, Environ. Model. Assess. 1 (1996) 119–135.

[12] N. Arnell, Climate change and global water resources: SRES scenarios and socio-economic scenarios, Glob. Environ. Change 14 (2004) 31–52.

[13] J. Alcamo, P. Döll, T. Heinrichs, F. Kaspar, B. Lehner, T. Rösch, S. Siebert, Global estimates of water withdrawals and availability under current and future business-as-usual conditions, Hydrol. Sci. J. 48 (2003) 339–348.

[14] C.J. Vorosmarty, P.J. Green, J. Salisbury, R.B. Lammers, Global water resources: vulnerability from climate change and population growth, Science 289 (2000) 284–288.

[15] P. Döll, S. Siebert, Global modeling of irrigation water requirements, Water Resources Research 8 (4) (2001) 1029–1035.

[16] P. Döll, Impact of climate change and variability on irrigation requirements: a global perspective, Clim. Change 54 (2002) 269–293.

[17] M.L. Parry, C. Rosenzweig, A. Iglesias, M. Livermore, G. Fischer, Effects of climate change on global food production under SRES emissions and socio-economic scenarios, Glob. Environ. Change 14 (2004) 53–67.

[18] G. Fischer, M. Shah, H. van Velthuizen, Climate change and agricultural vulnerability, Special Report to the UN World Summit on Sustainable Development, Johannesburg 2002, IIASA, Laxenburg, 2002.

[19] G. Fischer, H. van Velthuizen, M. Shah, F.O. Nachtergaele, Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results, IIASA RR-02-02, IIASA, Laxenburg, 2002.

[20] M.L. Parry, C. Rosenzweig, A. Iglesias, G. Fischer, M.T.J. Livermore, Climate change and world food security: a new assessment, Global Environmental Change 9 (1999) 51–67.

[21] K. Riahi, A. Gruebler, N. Nakicenovic, Scenarios of long-term socio-economic and environmental development under climate stabilization, Technol. Forecast. Soc. Change 74 (2007) 887–935, doi:10.1016/j.techfore.2006.05.026.

[22] G. Fischer, K. Frohberg, M.A. Keyzer, K.S. Parikh, Linked National Models: A Tool for International Policy Analysis, Kluwer Academic Publishers, Amsterdam, 1988, 214 pp.

[23] USDA–NASS, Farm and Ranch Irrigation Survey (2003), Special Studies: Part 1, AC-02-SS-1, 2002 Census of Agriculture, National Agricultural Statistics Service, vol. 3, US Department of Agriculture, Washington DC, 2004.

[24] IPCC, Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.

[25] IPCC, Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2001.
[26] Ming Zhang, personal communication, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 2005.
[27] F. Chen, H. Tang, H. Zhang, C. Cai, Irrigation Water Use in China, CHINAGRO Working Paper, China Agricultural University, Beijing, China, 2005.
[28] K. Palanisami, Power pricing, groundwater extraction, use and management: comparison of Andhra Pradesh and Tamil Nadu States. Presentation for IWMI-TATA Water Policy Research Program, 2003 (online at http://www.iwmi.cgiar.org/iwmi-tata/index.asp?id=328).
[29] K. Palanisami, Economics of irrigation technology transfer and adoption, Irrigation Technology Transfer in Support of Food Security, FAO, Water Reports, vol. 14, FAO, Rome, 1997.
[30] E. Perry, Low-cost irrigation technologies for food security in Sub-Saharan Africa, Irrigation Technology Transfer in Support of Food Security, FAO, Water Reports, vol. 14, FAO, Rome, 1997.
[31] S. Postel, Pillar of Sand: Can the Irrigation Miracle Last? Norton, New York, 1999.

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