Journal of Hydrology 384 (2010) 198–217

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation

Stefan Siebert *, Petra Döll

Institute of Physical Geography, University of Frankfurt, Box 111932, 60054 Frankfurt (Main), Germany

ARTICLE INFO

Keywords:
Crop water requirement
Global crop water model
Virtual water content
Irrigation water use
Crop production
Crop yield

SUMMARY

Crop production requires large amounts of green and blue water. We developed the new global crop water model GCWM to compute consumptive water use (evapotranspiration) and virtual water content (evapotranspiration per harvested biomass) of crops at a spatial resolution of $5'$ by $5'$, distinguishing 26 crop classes, and blue versus green water. GCWM is based on the global land use data set MIRCA2000 that provides monthly growing areas for 26 crop classes under rainfed and irrigated conditions for the period 1998–2002 and represents multi-cropping. By computing daily soil water balances, GCWM determines evapotranspiration of blue and green water for each crop and grid cell. Cell-specific crop production under both rainfed and irrigated conditions is computed by downscaling average crop yields reported for 402 national and sub-national statistical units, relating rainfed and irrigated crop yields reported in census statistics to simulated ratios of actual to potential crop evapotranspiration for rainfed crops. By restricting water use of irrigated crops to green water only, the potential production loss without any irrigation was computed. For the period 1998–2002, the global value of total crop water use was 6685 km^3 yr^{-1}, of which blue water use was 1180 km^3 yr^{-1}, green water use of irrigated crops was 919 km^3 yr^{-1} and green water use of rainfed crops was 4586 km^3 yr^{-1}. Total crop water use was largest for rice (941 km^3 yr^{-1}), wheat (858 km^3 yr^{-1}) and maize (722 km^3 yr^{-1}). The largest amounts of blue water were used for rice (307 km^3 yr^{-1}) and wheat (208 km^3 yr^{-1}). Blue water use as percentage of total crop water use was highest for date palms (85%), cotton (39%), citrus fruits (33%), rice (33%) and sugar beets (32%), while for cassava, oil palm and cocoa, almost no blue water was used. Average crop yield of irrigated cereals was 442 Mg km^{-2} while average yield of rainfed cereals was only 266 Mg km^{-2}. Average virtual water content of cereal crops was 1109 m^3 Mg^{-1} of green water and 291 m^3 Mg^{-1} of blue water, while average crop water productivity of cereal crops was 714 g m^{-3}. If currently irrigated crops were not irrigated, global production of dates, rice, cotton, citrus and sugar cane would decrease by 60%, 39%, 38%, 32% and 31%, respectively. Forty-three per cent of cereal production was on irrigated land, and without irrigation, cereal production on irrigated land would decrease by 47%, corresponding to a 20% loss of total cereal production. The largest cereal production losses would occur in Northern Africa (66%) and Southern Asia (45%) while losses would be very low for Northern Europe (0.001%), Western Europe (1.2%), Eastern Europe (1.5%) and Middle Africa (1.6%). Uncertainties and limitations are discussed in the manuscript, and a comparison of GCWM results to statistics or results of other studies shows good agreement at the regional scale, but larger differences for specific countries.

Introduction

Humans have altered the biosphere and the global water cycle significantly by converting natural vegetation into cropland or pasture and by extracting water from surface or groundwater bodies to support crop production (Ellis and Ramankutty, 2008; Rost et al., 2008; Scanlon et al., 2007). At the global scale, conversion to agricultural land has resulted in a decrease of evapotranspiration and an increase of river discharge (Rost et al., 2008). Consumptive crop water use (evapotranspiration) of green water and blue water has increased with the extension of agricultural land, and irrigated areas in particular (Klein Goldewijk and Ramankutty, 2004; Freydank and Siebert, 2008; L'vovich and White, 1990). We define consumptive blue crop water use as the amount of evapotranspiration on cropland stemming from irrigation. This water was extracted from surface or subsurface water bodies (e.g. streams, reservoirs, lakes, aquifers). Consumptive green crop water use is evapotranspiration stemming from precipitation on crop-

---

* Corresponding author. Address: Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany. Tel.: +49 (0) 228 733262; fax: +49 (0) 228 732870.

E-mail addresses: s.siebert@uni-bonn.de (S. Siebert), p.doell@em.uni-frankfurt.de (P. Döll).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2009.07.031

land. Total consumptive crop water use is the sum of consumptive blue crop water use and consumptive green water use and represents total actual crop evapotranspiration. Global food trade increasingly links consumers to crop water uses in distant production regions via so-called virtual water flows (Allan, 2003). Because of these virtual water flows, access to water resources, even to blue water, is not limited anymore by the boundaries of the watershed in which people are living. This helps to relax water scarcity in many arid regions but establishes at the same time dependencies on external resources. Quantification of these virtual water flows requires computation of crop- and climate-specific water uses. Chapagain and Hoekstra (2004) computed virtual water content (water use per harvested biomass) and virtual water trade for 175 crops and 210 countries, but their approach has several shortcomings. First, they use country averages of climate variables, which is particularly problematic in large countries with both humid and semi-arid areas like China and the USA. Second, they should overestimate crop water use as they assume no water limitation even in rainfed agriculture. Third, they do not distinguish the use of blue and green water. Such a distinction is very important due to the different opportunity costs of blue and green water uses. For example, only blue water use from irrigation is in direct competition with water use by households and industry.

Only very few models can compute crop-specific blue and green virtual water contents at the global scale. The resolution of these models ranges from 282 sub-basins in Impact-Water (Cai and Rosegrant, 2002), 1° in H07 (Hanasaki et al., 2008), 0.5° in GEPIC (Liu, 2009; Liu et al., 2007) and LPJmL (Rost et al., 2008; Bondeau et al., 2007), 0.1° in WATERSIM (De Fraiture, 2007) to 5′ in a model applied by FAO for 90 developing countries (Bruinsma, 2003). The quality of the output of these models strongly depends on the assumed growing areas and cropping seasons of the specific crops, and how well irrigated and rainfed crop production is distinguished. LPJmL, H07 and GEPIC used the data set of Leff et al. (2004) that indicates which fraction of each 5′ cell was covered by one of 100 crops (Leff et al., 2004). The data set was developed by downscaling census-based statistics for rather large statistical units. In this data set, the distribution of crops is similar in all grid cells belonging to the same statistical unit. Additionally, all crops within a statistical unit had a similar cropping intensity. Since the land use data set does not distinguish irrigated and rainfed crops, it was assumed in LPJmL that certain crops are more likely irrigated than others. In H07, the cropping pattern in irrigated and rainfed agriculture was assumed to be rather similar, while in GEPIC reported blue agricultural water uses per country were distributed equally over the area equipped for irrigation. In WATERSIM, harvested crop areas were simulated for 282 Food Processing Units using a partial-equilibrium agricultural production and trade model. Irrigated and rainfed harvested areas were then defined by using country-specific data available at FAO. All the models used different versions of the Global Map of Irrigation Areas (Siebert et al., 2006) to define area equipped for irrigation, while cropping periods and crop yields were simulated. Attempts to improve the land use and cropping information by using recently published, more suitable data sets (e.g. Monfreda et al., 2008; Ramankutty et al., 2008; Portmann et al., 2008) are documented for LPJmL, H07 and GEPIC in other contributions to this special issue of the journal.

Here, we present the global crop water model (GCWM) which computes crop-specific consumptive water uses of blue and green water, and virtual water contents at a 5′ resolution. GCWM is the first model to use the agricultural land use data set MIRCA2000 that provides growing areas and cropping periods for 26 different irrigated and rainfed crop classes. (Portmann et al., 2008, submitted for publication). MIRCA2000 covers the total global crop production and represents multi-cropping. GCWM determines daily soil water balances and thus evapotranspiration for each crop and grid cell, consistently identifying blue and green water. Cell-specific crop production under both rainfed and irrigated conditions is computed by downscaling average crop yields reported for 402 national and sub-national statistical units, relating rainfed and irrigated crop yields reported in census statistics to simulated ratios of actual to potential crop evapotranspiration for rainfed crops. Crop water uses, crop production, virtual water contents and crop water productivities were computed for each crop and each grid cell for the period 1998–2002. In an alternative simulation, water use of irrigated crops was restricted to green water only, and the resulting production loss was determined. The computed variables will become available for download at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/GCWM/index.html.

In the next section we describe the input data used by GCWM and the methodology to compute crop evapotranspiration, irrigated and rainfed crop yields, blue and green virtual water contents, crop water productivity and the production loss that would occur without irrigation. Then, we show the computed results (Section "Results"). In Section "Discussion", we discuss major limitations and uncertainties of GCWM, and compare the results to water use statistics and outputs of other models. In the last section we draw conclusions and describe first ideas for model improvements.

Data and methods

In this section we first describe the data used as input for GCWM, the growing areas and cropping seasons of irrigated and rainfed crops (Section "Growing areas and cropping seasons") and the climate and soil data (Section "Climate and soil data"). Then, we explain the methodology used in GCWM to compute consumptive crop water use (Section "Modeling of crop-specific blue and green consumptive water uses"), irrigated and rainfed crop production, potential production losses without irrigation (Section "Modeling of irrigated and rainfed crop productions and potential production losses without irrigation"), and virtual water content of crops and crop water productivity (Section "Virtual water content and crop water productivity"). In Section "Simulation protocol", we provide additional information on the simulation protocol.

Growing areas and cropping seasons

Growing areas of 26 crop classes (Table 1) and related cropping periods were derived from the MIRCA2000 data set (Portmann et al., 2008, submitted for publication). The data set covers all major food crops, cotton and unspecified other perennial, annual and fodder crops, and it distinguishes irrigated and rainfed crops. It was developed by combining a large amount of diverse national and sub-national statistical data, including grid layers of harvested crop area, cropland extent and area equipped for irrigation and cropping calendars. For GCWM, we used the MIRCA2000-Cropping Period Lists (CPL) that provide harvested area, start and end of cropping periods for each 5′ grid cell and for each of the 26 irrigated and rainfed crop classes. For annual crops, up to five so-called sub-crops were distinguished in MIRCA2000. Sub-crops can represent multi-cropping systems (e.g. double cropping or triple cropping of rice in southern Asia), winter and spring varieties of temperate cereals or specific sub-groups of a crop class that grow during different parts of the year (e.g. tobacco, different vegetables in group "others annual"). The data set is available for download at: http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html.

Climate and soil data

The procedure to assemble the climate input data at the required spatial and temporal resolution is described in detail in Sie-

Table 1
Length of crop development stages as fraction of the whole growing period for initial (*L_ini*), crop development (*L_dev*), mid season (*L_mid*) and late season (*L_late*), crop coefficients for initial period (*kc_ini*), mid season (*kc_mid*) and at the end of season (*kc_end*), rooting depth (*rd*) and standard crop depletion fraction (p_{std}) for the 26 crop classes considered in the global crop water model (GCWM).

Crop class	Relative length of crop development stage (–)				Crop coefficients (–)			Rooting depth *rd* (m)		p_{std} (–)
	L_ini	*L_dev*	*L_mid*	*L_late*	*kc_ini*	*kc_mid*	*kc_end*	Irrigated	Rainfed	
Wheat (1)	0.15	0.25	0.40	0.20	0.40	1.15	0.30	1.25	1.60	0.55
Maize (2)	0.17	0.28	0.33	0.22	0.30	1.20	0.40	1.00	1.60	0.55
Rice (3)	0.17	0.18	0.44	0.21	1.05	1.20	0.75	0.50	1.00	0.00
Barley (4)	0.15	0.25	0.40	0.20	0.30	1.15	0.25	1.00	1.50	0.55
Rye (5)	0.10	0.60	0.20	0.10	0.40	1.15	0.30	1.25	1.60	0.55
Millet (6)	0.14	0.22	0.40	0.24	0.30	1.00	0.30	1.00	1.80	0.55
Sorghum (7)	0.15	0.28	0.33	0.24	0.30	1.10	0.55	1.00	1.80	0.55
Soybeans (8)	0.15	0.20	0.45	0.20	0.40	1.15	0.50	0.60	1.30	0.50
Sunflower (9)	0.19	0.27	0.35	0.19	0.35	1.10	0.25	0.80	1.50	0.45
Potatoes (10)	0.20	0.25	0.35	0.20	0.35	1.15	0.50	0.40	0.60	0.35
Cassava (11)	0.10	0.20	0.43	0.27	0.30	0.95	0.40	0.60	0.90	0.35
Sugar cane (12)	0.00	0.00	1.00	0.00	0.00	0.90	0.00	1.20	1.80	0.65
Sugar beets (13)	0.20	0.25	0.35	0.20	0.35	1.20	0.80	0.70	1.20	0.55
Oil palm (14)	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.70	1.10	0.65
Rapeseed (15)	0.30	0.25	0.30	0.15	0.35	1.10	0.35	1.00	1.50	0.60
Groundnuts (16)	0.22	0.28	0.30	0.20	0.40	1.15	0.60	0.50	1.00	0.50
Pulses (17)	0.18	0.27	0.35	0.20	0.45	1.10	0.60	0.55	0.85	0.45
Citrus (18)	0.16	0.25	0.33	0.26	0.80	0.80	0.80	1.00	1.30	0.50
Date palm (19)	0.00	0.00	1.00	0.00	0.95	0.95	0.95	1.50	2.20	0.50
Grapes (20)	0.30	0.14	0.20	0.36	0.30	0.80	0.30	1.00	1.80	0.40
Cotton (21)	0.17	0.33	0.25	0.25	0.35	1.18	0.60	1.00	1.50	0.65
Cocoa (22)	0.00	0.00	1.00	0.00	1.05	1.05	1.05	0.70	1.00	0.30
Coffee (23)	0.00	0.00	1.00	0.00	1.00	1.00	1.00	0.90	1.50	0.40
Others perennial (24)	0.00	0.00	1.00	0.00	0.00	0.80	0.00	0.80	1.20	0.50
Fodder grasses (25)	0.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.50	0.55
Others annual (26)	0.15	0.25	0.40	0.20	0.40	1.05	0.50	1.00	1.50	0.55

bert and Döll (2008). Here, we limit ourselves to a short overview. Time series of monthly precipitation, number of wet days, mean temperature, diurnal temperature range and cloudiness were provided at a spatial resolution of 30′ by 30′ (Mitchell and Jones, 2005, available at http://www.cru.uea.ac.uk/cru/data/). To get closer to the required 5′ by 5′ resolution, we combined the time series data with monthly long-term averages at a resolution of 10′ by 10′ for precipitation, number of wet days, diurnal temperature range, sun shine percentage, wind speed and relative humidity (New et al., 2002) and elevation at 5′ resolution from the ETOPO-5 data set (NOAA, 1988) available at: http://www.ngdc.noaa.gov/mgg/global/etopo5.html. Disaggregation of monthly to daily values was done as follows: synthetic daily values of wind speed, sunshine percentage, maximum temperature, minimum temperature and mean temperature were interpolated from monthly values by applying cubic splines (Press et al., 1992). Daily precipitation was simulated by generating a sequence of dry and wet days using the monthly number of wet days (Geng et al., 1986) and distributing monthly precipitation equally over all wet days.

Calculation of soil water balances (see next section) required data on soil water capacity in the effective root zone. We used data on available water capacity from version 1.1 of ISRIC-WISE derived soil properties on a 5′ by 5′ global grid (Batjes, 2006) available at http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/WISE5by5minutes.htm.

Modeling of crop-specific blue and green consumptive water uses

Blue and green consumptive water uses were simulated by performing soil water balances for each sub-crop in each 5′ grid cell in daily time steps. The soil water balances are of the following general form:

$$\Delta S = P_{eff} + I - R - ET \tag{1}$$

where ΔS is the change of the soil moisture content within the effective root zone (mm day^{-1}), P_{eff} the amount of precipitation entering the soil (mm day^{-1}), I the irrigation water application (mm day^{-1}), R the runoff (mm day^{-1}), and ET is the evapotranspiration (mm day^{-1}). P_{eff} is computed as difference between daily precipitation P (mm day^{-1}) and the change of the water equivalent stored as snow $\Delta Snow$ (mm day^{-1}):

$$P_{eff} = P - \Delta Snow \tag{2}$$

where $\Delta Snow$ is assumed to be equal to P if mean daily temperature is below 0 °C (i.e. precipitation falls as snow and there is no melting of snow). Snow melting is simulated by multiplying mean daily temperature by a day-degree-factor of 4 mm °C^{-1} on days when mean daily temperature is above 0 °C. For irrigated crops, irrigation water is assumed to be applied to the soil if $S < (1 - p)\,S_{max}$, where S_{max} is the total available soil water capacity within the effective root zone (mm) and p (–) is a crop-specific depletion fraction (Allen et al., 1998; Eq. (9)). S_{max} is computed by multiplying the available water capacity by crop-specific rooting depth (Table 1). Irrigation water application I is assumed to be equal to the difference between actual soil moisture S and the total available soil water capacity S_{max}. Runoff R was computed as:

$$R = (P_{eff} + I)(S/S_{\max})^{\gamma_r} \tag{3}$$

Lower values for the parameter γ_r increase runoff and higher values decrease runoff. Since irrigated land is usually flat and in many cases covered with irrigation basins, surface runoff will be lower than on average. Therefore, the parameter γ was set to three for irrigated land and to two for rainfed areas. Reference evapotranspiration (ET_0) can be simulated in GCWM using the FAO Penman–Monteith approach (Allen et al., 1998)

$$ET_0\_PM = \frac{\Delta}{\Delta + \gamma(1 + 0.33u_2)}(R_n - G) + \frac{\gamma}{\Delta + \gamma(1 + 0.33u_2)} \times \frac{900}{T_{mean} + 273} u_2(e_s - e_a) \tag{4}$$

or the Priestley–Taylor method (Priestley and Taylor, 1972) modified according to Shuttleworth (1993)

$$ET_0\_PT = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{5}$$

where ET_0_PM is the reference evapotranspiration according to FAO Penman–Monteith in mm day^{-1}, ET_0_PT the reference evapotranspiration according to Priestley–Taylor in mm day^{-1}, Δ the slope of the vapor pressure curve in kPa °C^{-1}, γ the psychrometric constant in kPa °C^{-1}, u_2 the wind speed at 2 m height in m s^{-1}, R_n the net radiation at the crop surface in mm day^{-1}, G the soil heat flux in mm day^{-1}, T_{mean} the daily mean temperature in °C, e_s the saturation vapor pressure in kPa, e_a the actual vapor pressure in kPa and α is a dimensionless scaling coefficient. The procedure of computing ET_0 in GCWM is documented in detail in Siebert and Döll (2008).

Potential daily crop evapotranspiration *PETc* (mm day^{-1}) is the evapotranspiration of a crop that is healthy and well-watered. It depends on crop type and crop development stage and is computed as

$$PETc = k_c ET_0 \tag{6}$$

where k_c is the crop coefficient (–). The parameters needed to establish the daily crop coefficients (Table 1) were defined according to Allen et al. (1998). Within the initial crop development stage, crop coefficients are constant at the level of k_c_ini. During crop development, crop coefficients increase at constant daily rates to the level given by k_c_mid. In the mid season period, crop coefficients are constant at the level of k_c_mid, and in the late season stage, crop coefficients are assumed to change in constant steps to the value given by k_c_end (Fig. 1). For perennial crops the crop coefficient is kept constant at the level of k_c_mid. The total length of the growing season is derived from the MIRCA2000 data set (Portmann et al., 2008, submitted for publication) and depends on the specific crop and the spatial unit. The actual evapotranspiration of crops *AETc* is computed according to Allen et al. (1998) as

$$AETc = k_s PETc \tag{7}$$

with

$$k_s = \begin{cases} \frac{S}{(1-p)S_{\max}} & \text{if } S < (1-p)S_{\max} \\ 1 & \text{otherwise} \end{cases} \tag{8}$$

where k_s is a dimensionless transpiration reduction factor dependent on available soil water. Crop-specific depletion fraction p refers to the fraction of S_{max} that a crop can extract from the root zone without suffering water stress. It is a function of crop type and potential crop evapotranspiration and is computed according to Allen et al. (1998) as

$$p = p_{std} + 0.04(5 - PETc) \tag{9}$$

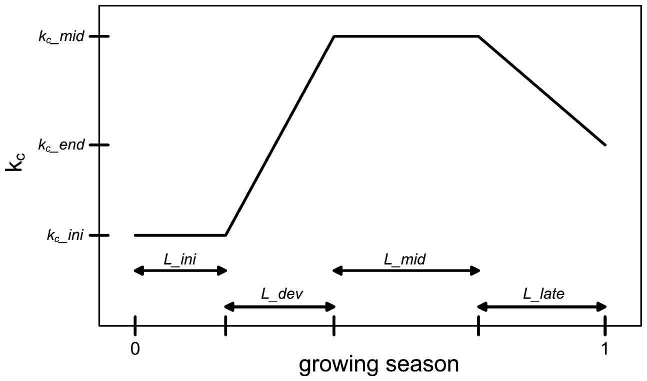

Fig. 1. Construction of a crop coefficient curve based on parameters listed in Table 1.

where p_{std} is a crop-specific depletion fraction valid for an evapotranspiration level of about 5 mm day^{-1} derived from Allen et al. (1998) and documented in Table 1. The equation implies that a crop may suffer water stress even at a relatively high soil moisture level if the evaporative power of the atmosphere is high.

To compute the consumptive water use of specific crops and sub-crops, the general notation of the soil water balance (1) was modified depending on whether sub-crops were grown on area equipped for irrigation (AEI) or not and depending on whether sub-crops were irrigated or rainfed (Fig. 2). In general it was assumed that irrigated sub-crops were grown on AEI as defined by Siebert et al. (2006) while rainfed permanent crops were grown on areas not equipped for irrigation (ANEI) defined as difference between total cropland extent (Portmann et al., submitted for publication) and AEI. In contrast, rainfed annual crops were grown on ANEI but also on AEI if the AEI was not completely occupied by irrigated crops (Fig. 2). The difference of cropped AEI to total AEI and cropped ANEI to total ANEI was fallow land represented by a rainfed grass crop with a constant k_c of 0.5 and a rooting depth of 1 m. At the start of a cropping season of an annual sub-crop, fallow land was reduced by the growing area of the sub-crop and the soil water storage of the sub-crop was initialized by using the relative moisture content on fallow land. At the end of the sub-crop growing season fallow land was increased by the growing area of the sub-crop and the soil moisture content under fallow land was set to the area weighted average soil moisture.

For irrigated sub-crops, the two water balances WB_IR1 and WB_IR2 are computed (Fig. 2). In WB_IR1, irrigation water is applied such that crop evapotranspiration is always at its potential level while in WB_IR2 irrigation water is not applied so that crop evapotranspiration drops to water-limited *AETc*. The consumptive water use of green water *CWU_G* (mm day^{-1}) is then set to *AETc* computed in WB_IR2, and the consumptive water use of blue water CWU_B (mm day^{-1}) is set to the difference between *PETc* computed in WB_IR1 and *AETc* computed in WB_IR2. Thus, CWU_B represents the amount of water that additionally evapotranspirates if irrigation increases water-limited *AETc* to *PETc*. It is therefore different from irrigation water application *I* described before, also because a fraction of *I* becomes runoff (Eq. (3)).

For rainfed crops and fallow land on ANEI only one soil water balance WB_RF2 was computed. The difference of WB_RF2 to WB_IR2 is that the rooting depth (Table 1) and the parameter γ_r in the runoff calculation (3) are set to the values for rainfed crops. *CWU_G* is set to *AETc* while CWU_B is set to 0.

If AEI is fallow or covered by rainfed annual crops, a small amount of blue water use could occur in addition to green water use if some irrigation water applied to irrigated crops grown before is still stored in the soil. To account for this minor effect, the water balance WB_RF1 was computed in addition to WB_RF2. The difference between these balances is that soil moisture storage is initialized at the start of the cropping season using the soil moisture content of fallow land on AEI in WB_RF1, and of fallow land on ANEI in WB_RF2. In these cases, CWU_B is the difference between *AETc* computed in WB_RF1 and *AETc* computed in WB_RF2 while *CWU_G* was again set to *AETc* computed in WB_RF2 (Fig. 2).

Modeling of irrigated and rainfed crop productions and potential production losses without irrigation

Crop yield is defined as crop production per harvested crop area. Since application of irrigation water reduces water stress of crops, crop yields are usually larger in irrigated agriculture than in rainfed agriculture. To our knowledge there are, however, only a few agricultural statistics that report crop yields separately for irrigated and rainfed agriculture. Therefore, we estimated the cell- and crop-specific ratio between rainfed crop yield and irrigated

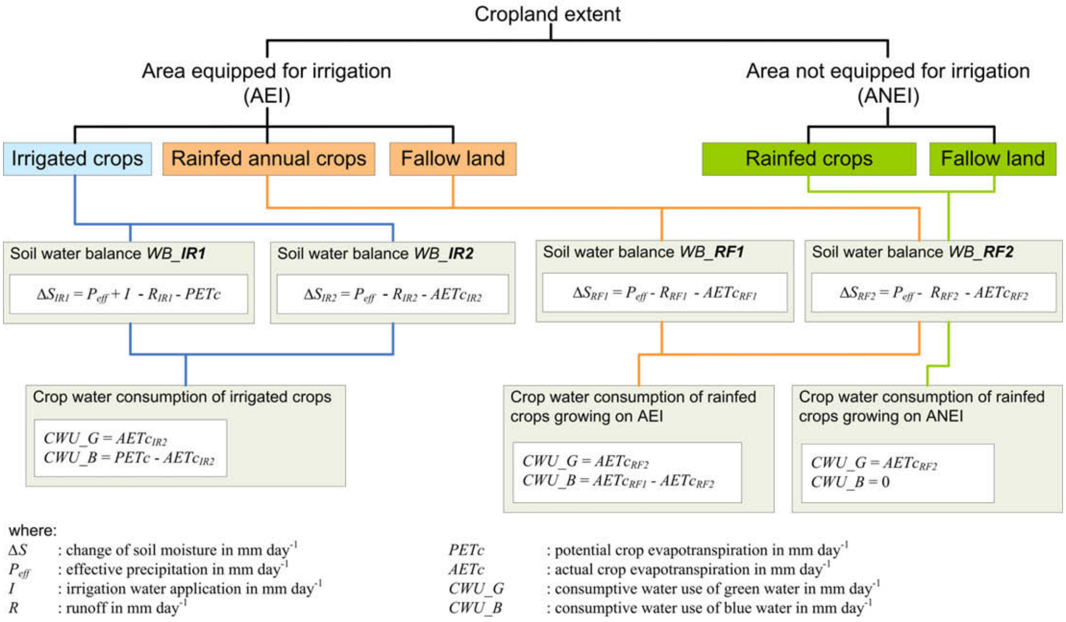

Fig. 2. Schematic representation of soil water balances performed for irrigated crops, rainfed crops and fallow land to compute consumptive use of blue and green water in crop production. WB_RF1 differs from WB_RF2 by the initialization of soil moisture while in the irrigated water balances WB_IRx two model parameter differ from those in the rainfed water balances WP_RFx (see text).

crop yield *YR*/*YI* based on the ratio between actual and potential crop evapotranspiration of rainfed crops (*AET*/*PET*) as follows:

$$YR/YI = \begin{cases} 1 \quad \text{if } a(AET/PET) + b > 1 \\ aP1 + b - \left[(P1 - (AET/PET))^{*} \frac{aP1+b}{P1-P0}\right] \\ \quad \text{if } P0 < (AET/PET) < P1 \\ 0 \quad \text{if } (AET/PET) \leqslant P0 \\ a(AET/PET) + b \quad \text{else} \end{cases} \tag{10}$$

where *a*, *b*, *P0* and *P1* are crop-specific parameters derived from a comparison of the observed *YR*/*YI* ratios to *AET*/*PET* ratios computed by GCWM for the same reference year (Fig. 3), based on statistical data for Iran (Ministry of Jahad-e-Agriculture, 2008), Lao PDR (Ministry of Agriculture and Forestry, 2006) and the USA (USDA, 1999). When *YR*/*YI* observations were not available for specific crops, slope parameter *a* was set to one, and offset *b* was set to −0.1 for aquatic crops (rice, sugar cane) and to values between 0 and 0.1 for the other crops. Parameter *P0* was set to 0.1 for most crops (Table 2). These yield ratios are computed for each grid cell and each crop, and an average yield ratio $\overline{YR/YI}$, weighted by harvested area per grid cell, is computed for each of the 402 spatial units used in MIRCA2000 and delineated in Fig. 4.

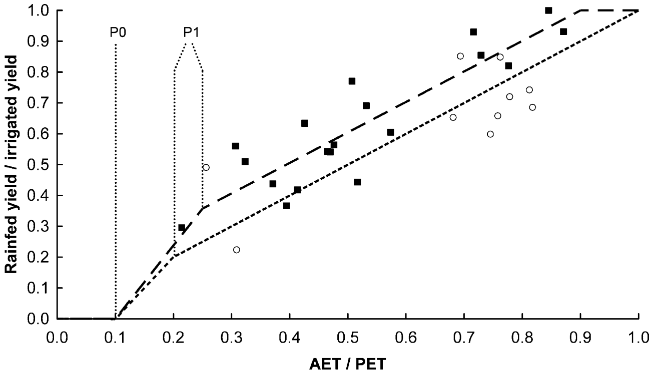

Fig. 3. Two examples for deriving the function that relates the ratio of rainfed crop yield and irrigated crop yield (*YI*/*YR*) to the ratio of actual evapotranspiration and potential evapotranspiration (*AET*/*PET*) (Eq. (10)). Data reported for wheat (solid squares) and cotton (open circles) for federal states of the US in 1998 and functions derived to compute the ratio (*YI*/*YR*) for wheat (long lined graph) and cotton (short lined graph) by applying the parameters listed in Table 2.

Since total crop production can be expressed as

$$AHT^{*}\ \overline{YT} = AHI^{*}\ \overline{YI} + AHR^{*}\ \overline{YR} \tag{11}$$

where *AHT*, *AHI* and *AHR* were total, irrigated and rainfed harvested crop area per spatial unit ($\text{km}^2\ \text{yr}^{-1}$) and $\overline{YT}$, $\overline{YI}$ and $\overline{YR}$ were average total, irrigated and rainfed crop yield per spatial unit (Mg km^2), it was possible to compute average irrigated yield $\overline{YI}$ by rearrangement of Eq. (11) as

$$\overline{YI} = \overline{YT}\left(\frac{AHT}{AHI + (\overline{YR/YI})AHR}\right) \tag{12}$$

Harvested areas *AHT*, *AHI* and *AHT* were derived from the MIRCA 2000 data set (Portmann et al., 2008, submitted for publication) while $\overline{YT}$ was derived from Monfreda et al. (2008). Finally, cell- and crop-specific rainfed yield was computed by assuming that irrigated yield *YI* was constant and equal to $\overline{YI}$ for all grid cells belonging to the same spatial unit, and by multiplying *YI* with the cell-specific ratio *YR*/*YI* (Eq. (10)). Irrigated and rainfed crop production was calculated by multiplying yields with related harvested areas. To avoid that the calculation procedure resulted in unrealistically large crop yields, maximum possible yields per spatial unit and per grid cell were defined for each crop (Table 2). If computed yields were larger than maximum yields, these yields were reduced, and yields in other grid cells were scaled so that $\overline{YT}$ in the spatial unit was equal to the value derived from Monfreda et al. (2008). If irrigated harvested crop area was 0 in a spatial unit while harvested rainfed crop area was larger than 0, a special treatment was required. Instead of using the computed irrigated yield *YI* (0 in this case) we used the maximum crop yield (Table 2) to compute *YR*, and reduced the computed cell specific yields afterwards by using a constant scaling coefficient such that $\overline{YT}$ was equal to the Monfreda value.

Table 2
Parameters used in the global crop water model (GCWM) to compute irrigated and rainfed crop yields.

Crop class	Parameters used to estimate the *YR*/*YI* ratio (–)				Maximum yield (Gg km^2)	
	a	*b*	*P0*	*P1*	Per spatial unit	Per grid cell
Wheat	0.9885	0.1103	0.10	0.25	1.00	1.20
Maize (grain)	1.2929	−0.0798	0.10	0.40	2.40	2.83
Rice	1.0000	−0.1000	0.10	0.50	1.20	1.57
Barley	1.4780	−0.4288	0.10	0.50	0.80	1.00
Rye (grain)	1.0000	0.1000	0.10	0.50	0.75	0.95
Millet	1.0000	0.1000	0.10	0.50	0.80	0.90
Sorghum (grain)	0.8681	0.2753	0.10	0.30	1.50	1.70
Soybeans	0.8373	0.2080	0.10	0.40	0.40	0.90
Sunflower	1.0000	0.0000	0.10	0.50	0.40	0.70
Potatoes	1.0000	0.1000	0.10	0.50	7.00	9.00
Cassava	1.0000	0.1000	0.15	0.50	4.00	4.50
Sugar cane	1.0000	−0.1000	0.10	0.50	15.00	16.00
Sugar beets	1.0000	0.1000	0.10	0.50	9.00	9.50
Oil palm	1.0000	0.0000	0.10	0.50	3.20	5.00
Rapeseed	1.0000	0.1000	0.10	0.50	0.50	0.60
Groundnuts	1.0000	0.0000	0.10	0.50	0.85	1.20
Pulses	1.3000	−0.2000	0.10	0.50	0.60	0.85
Citrus	1.0000	0.0000	0.15	0.50	4.00	6.40
Date palm	1.0000	0.1000	0.05	0.30	4.00	4.50
Grapes	1.0000	0.1500	0.05	0.30	4.00	4.60
Cotton	1.0000	0.0000	0.10	0.20	0.55	1.20
Cocoa	1.0000	0.1000	0.15	0.60	0.15	0.30
Coffee	1.0000	0.1000	0.15	0.60	0.60	1.00
Others perennial	1.2000	−0.1000	0.10	0.50	4.00	6.00
Fodder grasses	1.0000	0.0000	0.05	0.20	10.00	12.00
Others annual	1.2000	−0.1000	0.10	0.50	5.00	7.00
Maize (forage)	1.2929	−0.0798	0.10	0.40	6.50	9.40
Rye (forage)	1.0000	0.1000	0.10	0.50	4.50	9.00
Sorghum (forage)	0.8681	0.2753	0.10	0.30	7.00	8.00

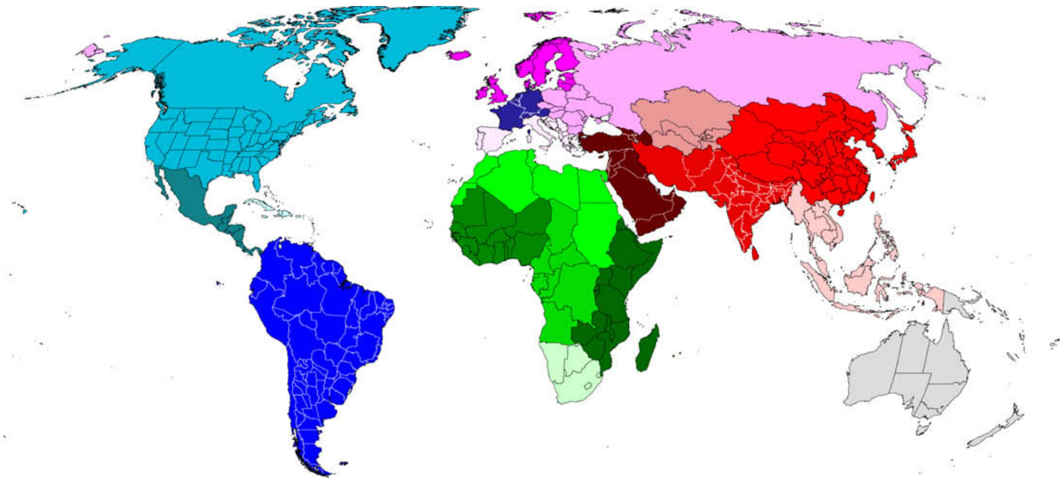

Fig. 4. Four hundred and two national and sub-national spatial units, and 19 FAO world regions in Africa (green tones), America (blue) Asia (red) and Europe and Russia (pink) (plus Oceania, grey) as used in this publication. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The parameters *a*, *b*, *P0* and *P1* used in Eq. (10) are sensitive to the method used to compute ET_0. Therefore, we determined a parameters set by using the Penman–Monteith method to compute ET_0 (Table 2, Fig. 3) and another one by using the Priestley–Taylor method (not shown here).

To calculate the production loss that would occur without irrigation *PLNI* (%), we computed crop production under the assumption that no irrigation water was applied to irrigated crops. Thus irrigated yields were reduced according to Eq. (10) and *PLNI* was calculated as follows:

$$PLNI = 100^{*}(PT_{noirrig} - PT)/PT \tag{13}$$

where *PT* is crop production if irrigation water is applied to irrigated crops (Mg yr^{-1}), and $PT_{noirrig}$ is crop production if no irrigation water is applied to irrigated crops (Mg yr^{-1}). *PLNI* was either computed considering irrigated crops only, thus quantifying the impact of irrigation on crop yields in irrigated areas, or considering total irrigated and rainfed crop production, thus quantifying the effect of irrigation on total crop production.

Virtual water content and crop water productivity

The virtual water content of a crop is the amount of water needed to produce a unit of harvested crop and is computed as:

$$VWC\_T = CWU\_T/PT \tag{14}$$

where *VWC_T* is the virtual water content of a crop (m^3 Mg^{-1}), *CWU_T* the total consumptive water use of a crop (m^3 yr^{-1}) and

PT is the total crop production (Mg yr^{-1}). Virtual water content was further partitioned in virtual blue water content VWC_B (m^3 Mg^{-1}) and virtual green water content VWC_G (m^3 Mg^{-1}) by dividing blue or green consumptive water use by total crop production PT. VWC can become very large or even infinity, for example, in case of crop failure. Crop water productivity expresses the amount of harvested crop that can be achieved per unit of crop water use, and is calculated as the reciprocal value of VWC:

$$CWP = PT/CWU\_T \tag{15}$$

where CWP is the crop water productivity (Mg m^{-3}).

Simulation protocol

The model was applied for the period 1998–2002 because the input data on growing areas and cropping seasons only existed for this period. While the climate input consisted of time series between January 1997 and December 2002, land cover was kept constant. To allow a proper initialization of the soil water storages the simulations were started in January 1997. Unless otherwise noted, the results presented in the following were obtained by computing reference evapotranspiration according to the FAO Penman–Monteith equation (see Section "Comparison to independent estimates of irrigation water withdrawals and consumptive use for reasons" for preferring the Penman–Monteith approach).

Results

Using GCWM we computed daily crop water uses of blue and green water for 26 irrigated and rainfed crops at the 5′ by 5′ resolution for the period 1998–2002. Here we present monthly and annual averages of crop water uses at the global scale, for continents, regions and at the grid cell level (Section "Crop water use of blue and green water"). Computed crop yields and crop production in irrigated and rainfed agriculture as well as potential production losses without irrigation are shown in Section "Crop yields, crop production and potential production losses without irrigation", and virtual water contents of green and blue water as well as crop water productivity in Section "Virtual water content and crop water productivity".

Crop water use of blue and green water

During the period 1998–2002, total consumptive crop water use was 6685 km^3 yr^{-1}. These totals include 43 km^3 yr^{-1} of blue water evapotranspirated outside the cropping season of irrigated crops (when the related cropland was fallow or cropped with rainfed crops), but they exclude green water evapotranspirated on fallow land. Irrigated crops consumed 1180 km^3 yr^{-1} of blue and 919 km^3 yr^{-1} of green water, while rainfed crops consumed 4586 km^3 yr^{-1} of green water (Table 3). Thus, about 56% of crop evapotranspiration of irrigated crops and 18% of total crop evapotranspiration was from blue water. Consumptive use of green water on fallow land, computed by using the global cropland extent of 16.0 million km^2 as provided by MIRCA2000 was 3137 km^3 yr^{-1} such that green water use in crop production including water use on fallow land was 9823 km^3 yr^{-1}.

Total crop water use and fractions of blue and green crop water consumption differed strongly between crops (Table 3), regions (Table 4) and at the 5′ grid scale (Fig. 5). The largest total crop

Table 3
Total harvested area (AHT), irrigated harvested area as percentage of total harvested crop area (AHI), blue crop water use (CWU_B), green crop water use of irrigated (CWU_G_IRC) and rainfed crops (CWU_G_RFC), blue crop water use as percentage of total crop water use (CWU_B_T) and crop water use of irrigated crops (CWU_B_I) for the crop classes considered in the global crop water model.

Crop	AHT (1000 km^2 yr^{-1})	AHI (%)	CWU_B (km^3 yr^{-1})	CWU_G_IRC (km^3 yr^{-1})	CWU_G_RFC (km^3 yr^{-1})	CWU_B_I (%)	CWU_B_T (%)
Wheat	2146	31.1	208.0	115.4	534.9	64.3	24.2
Maize (grain)	1367	20.0	72.4	92.0	493.3	44.1	11.0
Rice	1657	62.2	307.3	337.3	296.8	47.7	32.6
Barley	551	8.4	10.7	8.6	141.7	55.5	6.7
Rye (grain)	94	4.1	0.5	0.5	11.3	48.3	4.1
Millet	336	5.2	4.0	4.3	127.2	48.0	2.9
Sorghum (grain)	391	8.5	10.6	9.6	163.2	52.6	5.8
Cereals (grain)	6543	31.7	613.6	567.7	1768.5	51.9	20.8
Soybeans	748	8.1	17.3	25.0	357.1	40.8	4.3
Sunflower	208	6.1	4.1	3.5	64.1	54.2	5.7
Potatoes	197	19.0	13.5	8.4	53.0	61.6	18.0
Cassava	155	0.1	<0.05	<0.05	143.5	47.2	<0.05
Sugar cane	209	48.6	68.9	70.7	101.8	49.3	28.5
Sugar beets	62	25.4	9.1	3.0	16.8	75.5	31.5
Oil palm	97	0.1	<0.05	0.1	116.9	31.6	<0.05
Rapeseed	246	13.8	7.9	2.9	48.1	72.7	13.3
Groundnuts	227	16.2	7.6	13.1	77.0	36.6	7.7
Pulses	671	8.1	22.4	7.7	165.5	74.4	11.4
Citrus	75	47.6	23.2	17.4	28.8	57.1	33.4
Date palm	9	78.8	10.5	1.2	0.6	89.6	85.3
Grapes	71	24.2	7.1	5.0	20.3	58.9	22.0
Cotton	332	49.0	83.7	46.2	85.0	64.4	38.9
Cocoa	68	0.2	<0.05	0.1	65.9	19.6	<0.05
Coffee	102	1.7	1.1	1.4	100.2	43.9	1.1
Others perennial	731	17.6	83.8	56.0	458.8	59.9	14.0
Fodder grasses	1047	11.2	90.1	47.1	529.2	65.7	13.5
Others annual	1088	18.5	61.8	34.5	309.7	64.2	15.2
Maize (forage)	148	17.4	10.7	6.9	46.8	60.9	16.6
Rye (forage)	10	5.7	0.5	0.7	25.4	41.3	1.9
Sorghum (forage)	10	10.4	0.4	0.2	2.7	63.4	11.7
Total	13 053	23.9	1180.3	918.9	4585.9	56.2	17.7

Table 4
Total harvested area (AHT), irrigated harvested area as percentage of total harvested crop area (AHI), blue crop water use (CWU_B), green crop water use of irrigated (CWU_G_IRC) and rainfed crops (CWU_G_RFC), blue crop water use as percentage of total water use of irrigated crops (***CWU***_B_I), and blue crop water use as percentage of total crop water use (CWU_B_T), for continents and world regions.

Continent/region	AHT (1000 km^2 yr^{-1})	AHI (%)	CWU_B (km^3 yr^{-1})	CWU_G_IRC (km^3 yr^{-1})	CWU_G_RFC (km^3 yr^{-1})	CWU_B_I (%)	CWU_B_T (%)
Eastern	389	6.3	8.5	9.4	165.8	47.4	4.6
Middle	150	0.9	0.6	0.5	79.0	54.0	0.8
Northern	317	31.4	75.7	7.7	63.8	90.7	51.4
Southern	82	21.1	9.1	6.8	26.4	57.0	21.4
Western	737	0.9	4.3	2.2	403.4	66.3	1.1
Africa	1675	8.9	98.2	26.7	738.3	78.6	11.4
Caribbean	48	24.9	2.9	8.9	29.9	24.4	6.9
Central	224	29.0	28.1	28.3	90.0	49.8	19.2
Northern	1670	12.7	141.8	81.5	738.0	63.5	14.7
South	1009	8.6	29.5	39.7	542.2	42.6	4.8
America	2950	12.7	202.2	158.4	1400.1	56.1	11.5
Central	252	34.9	49.7	13.7	38.4	78.4	48.8
Eastern	1790	50.6	151.7	278.2	363.4	35.3	19.1
South-Eastern	968	24.8	52.8	121.8	543.9	30.2	7.3
Southern	2452	43.1	480.0	238.6	523.2	66.8	38.7
Western	341	32.2	73.5	15.0	65.5	83.0	47.7
Asia	5803	41.4	807.7	667.3	1534.4	54.8	26.8
Eastern + Russia	1490	4.0	17.4	20.6	545.5	45.8	3.0
Northern	181	2.8	0.3	1.6	70.3	17.6	0.5
Southern	363	22.8	36.3	23.4	95.4	60.8	23.4
Western	335	6.6	3.6	7.9	130.8	31.2	2.5
Europe + Russia	2368	7.1	57.7	53.5	841.9	51.9	6.1
Oceania	256	10.8	14.5	13.0	71.1	52.8	14.7
World	13 053	23.9	1180.3	918.9	4585.9	56.2	17.7

water use was computed for the crops rice (941 km^3 yr^{-1}), wheat (858 km^3 yr^{-1}) and maize (722 km^3 yr^{-1}) that also dominate the global harvested crop area (Table 3). Rice (307 km^3 yr^{-1}) and wheat (208 km^3 yr^{-1}) also consumed the largest total amount of blue water. The largest value of blue water use as percentage of total crop water use (*CWU_B_T*) was calculated for date palms (85%). In addition, *CWU_B_T* was larger than 30% for cotton (39%), citrus crops (33%), rice (33%) and sugar beets (32%). Crop water use was almost completely from green water for cassava, oil palm and cocoa. The percentage of total crop water use from blue water (*CWU_B_T*) depends on the percentage of the harvested crop area that is irrigated (*AHI*), on the percentage of blue water use of irrigated crops (*CWU_B_I*) and on the crop-specific total water use on irrigated and rainfed land. *AHI* was largest for date palm (79%), rice (62%), cotton (49%), sugar cane (49%) and citrus (48%), while the harvested crop area was almost completely rainfed for cassava (0.1%), oil palm (0.1%) and cocoa (0.2%). Twenty-four per cent of the total harvested crop area and 32% of the harvested cereals area was irrigated. *CWU_B_I* was largest for date palm (90%), lowest for cocoa (20%) and for most of the other crops between 40% and 70% (Table 3). Total crop water use is usually larger when a crop is irrigated because any water deficit can be met by irrigation so that the actual crop evapotranspiration is at its potential level. However, longer cropping seasons of rainfed crops partly compensate for this effect.

On the continental scale, total crop water use was 3009 km^3 yr^{-1} for Asia, 1761 km^3 yr^{-1} for America, 953 km^3 yr^{-1} for Europe (including Russia), 863 km^3 yr^{-1} for Africa and 99 km^3 yr^{-1} for Oceania. These values are mainly related to total harvested crop area (Table 4). Most blue water (808 km^3 yr^{-1}) was used in Asia which represents 68% of the global sum of blue water use (Table 4). Forty-one per cent of the harvested crop areas were irrigated in Asia, while the percentage of irrigated harvested crop area was between 7% and 13% for the other continents. At the regional scale, 51% of total crop water use was from blue water in Northern Africa, 49% in Central Asia, 48% in Western Asia, 39% in Southern Asia but less than 1% in Northern Europe and Middle Africa (Table 4). Similarly, blue crop water use as percentage of total water use of irrigated crops was largest in Northern Africa (91%), Western Asia (83%), Central Asia (78%) and Southern Asia (67%) but lowest in Northern Europe (18%).

The map of total crop water use (Fig. 5a) shows a pattern that is similar to the pattern of cropland extent (Ramankutty et al., 2008) or harvested crop area (Monfreda et al., 2008; Portmann et al., submitted for publication), which indicates that total crop water use is mainly determined by the fraction of harvested crop area per grid cell. Large areas of total crop water uses of more than 400 mm yr^{-1} (related to total grid cell area) occur in China, in the USA and in the Indus and Ganges basins of Pakistan, India and Bangladesh. Smaller regions of these large water use intensities are dispersed over the entire global land mask at latitudes between 50°N (60°N in Europe) and 40°S. Large areas without any significant crop water use are found at high latitudes, and in large parts of the deserts and tropical rainforests.

The percentage of blue crop water use on irrigated land *CWU_B_I* (Fig. 5b) correlates with aridity, with large values in the Western United States, along the west coast of South America (Peru, Chile), in Northern Africa, in the Near East and in Central Asia, and with low values in humid or temperate regions. Even in regions where almost all agriculture is irrigated, *CWU_B_I* may be below 50%, e.g. in the more humid paddy rice growing areas of South East China. The high percentages of blue crop water uses in extended areas in arid Northern and central Australia are artifacts introduced by using Global Map of Irrigation Areas (Siebert et al., 2006) for defining irrigated and rainfed crop areas (Portmann et al., submitted for publication). In the Global Map of Irrigation Areas, small areas of irrigation infrastructure reported for large administrative units in Central Australia were distributed equally

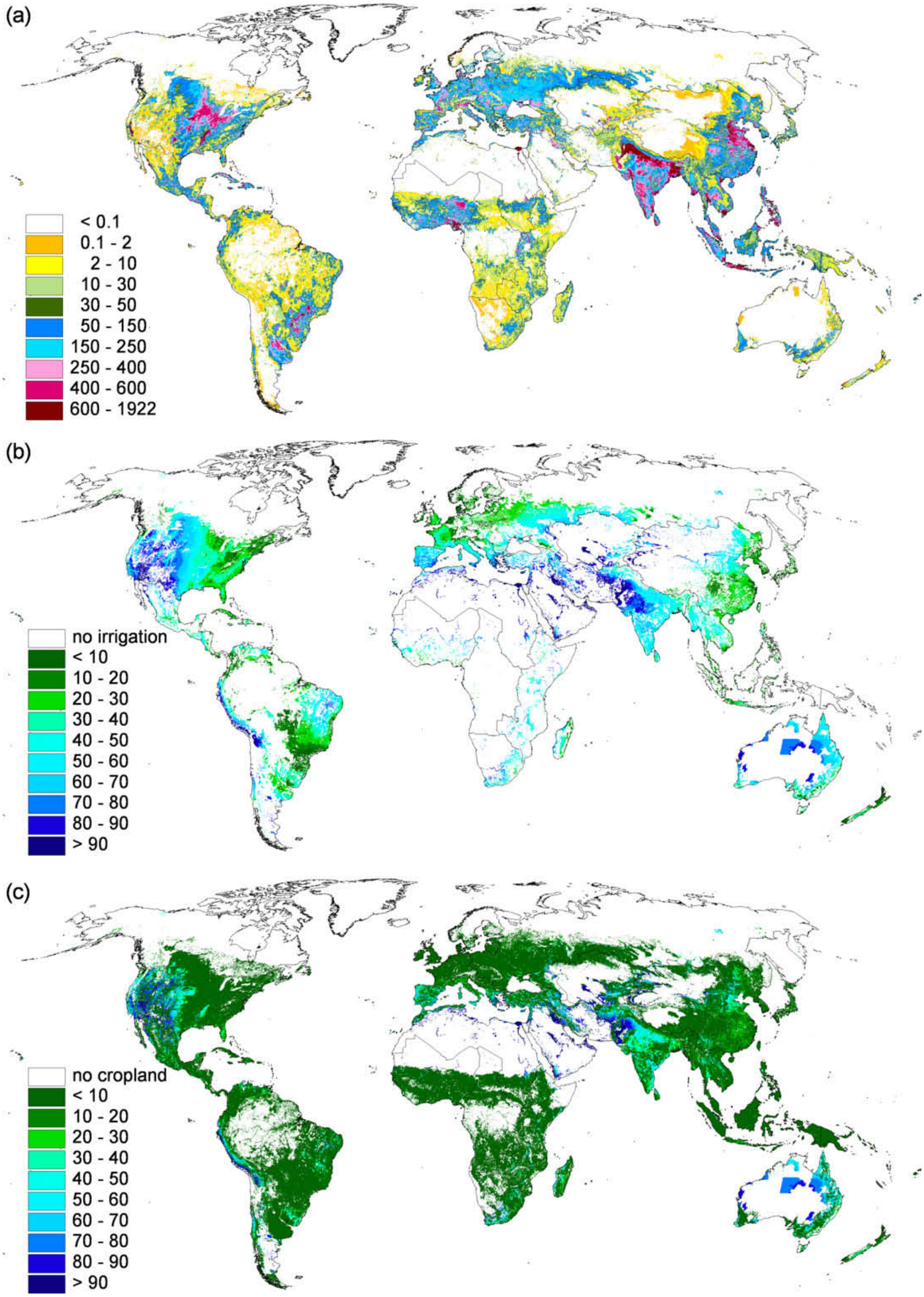

Fig. 5. Total consumptive crop water use in mm yr^{-1} (a) and percentage of blue crop water use on irrigated land (b) and on total cropland (c) as computed by the global crop water model for the period 1998–2002.

over the whole administrative units because geo-spatial information on the location of irrigation areas was missing. This resulted in very small irrigated areas in each grid cell. As rainfed agriculture does not exist there, very low total crop water uses (Fig. 5a) and high percentages of blue water use on irrigated land (Fig. 5b) and on total cropland (Fig. 5c) were computed for each grid cell. In reality, these irrigation water uses are very likely to be concentrated in very few places.

The percentage of blue crop water use on total cropland land *CWU_B_T* (Fig. 5c) shows that in most regions crop water use was predominantly from green water. This is also the case for many regions where relatively large values of *CWU_B_I* (Fig. 5b) indicate the usefulness of additional water application by irrigation, like Northeastern Brazil, Mexico or many regions of Sub-Saharan Africa. This shows that in these regions rainfed agriculture is dominant. Large values of *CWU_B_T* only occur in arid areas where agriculture is predominantly irrigated. In areas without any rainfed agriculture, percentages shown in Fig. 5c are equal to percentages shown in Fig. 5b.

Monthly global crop water uses of green water caused by rice and cotton had a peak in July/August in northern hemisphere summer, while green crop water use of wheat was largest in April and May and thus in northern hemisphere spring (Fig. 6). Monthly blue water use of irrigated rice showed two peaks from February to March and July to August. Blue water use of irrigated wheat was largest in March while blue water use of cotton was largest in August. The share of water uses for rice, wheat and cotton on total crop water use was much larger for blue water than for green water indicating the importance of these crops in irrigated agriculture. Furthermore, monthly crop water use of green water was more homogeneous throughout the year for wheat and cotton compared to the related blue water uses.

Crop yields, crop production and potential production losses without irrigation

The major cereal production areas were located in the northern United States, Western Europe, the North China Plain, Bangladesh and the Punjab region in India and Pakistan. Cereal production was remarkably low in South America and Africa with the exception of four cereal production centers located in Northeastern Argentina, Southeastern Brazil, the northern part of Nigeria and in South Africa north of Lesotho (Fig. 7a). Large percentages of cereal production were irrigated in all regions of Asia, the extended areas in the USA, along the west coast of South America, in Southern Brazil (Rio Grande do Sul), Northern Africa, Madagascar and in many parts of Southern Europe (Fig. 7b). Computed yields of rainfed cereals were largest in the maize production areas of the Northern United States (Iowa, Minnesota, Wisconsin and Illinois), in Western Europe and East China. Low rainfed cereal yields were computed for almost the entire Africa, Northern Mexico, Northwestern China, Western India and Pakistan (Fig. 7c).

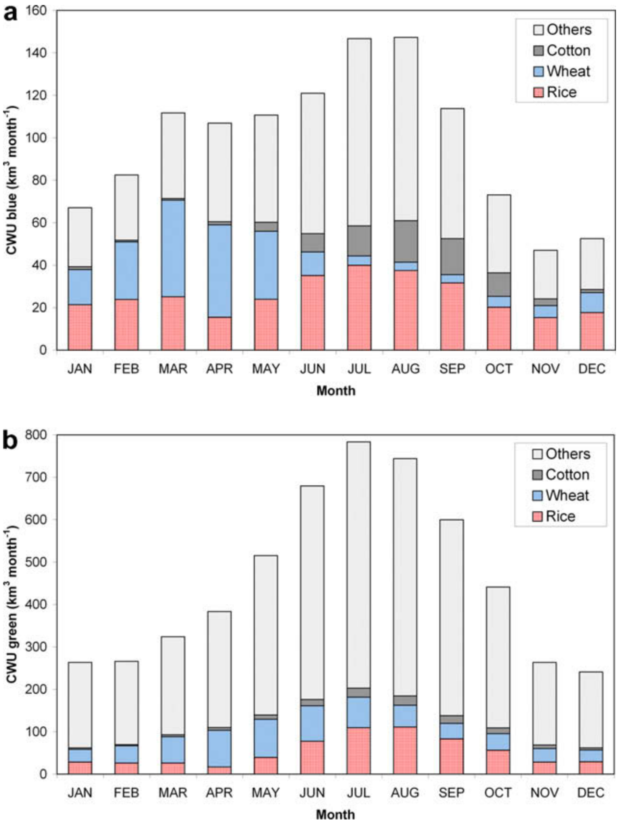

Fig. 6. Global averages of monthly consumptive water use of blue water (top) and green water (bottom) of rice wheat cotton and other crops in km^3 month^{-1} as computed by the global crop water model for the period 1998–2002.

For most of the crops average irrigated yields were larger than average rainfed yields (Table 5). Average crop yield of irrigated cereals was 442 Mg km^{-2} while average yield of rainfed cereals was only 266 Mg km^{-2}. The methodology used in GCWM ensures that, at the level of the spatial units, yields of irrigated crops were always larger or equal to the yields of the related rainfed crop, because irrigated crops did not face any water stress (see Section "Modeling of irrigated and rainfed crop productions and potential production losses without irrigation"). Nevertheless, global average rainfed yield was larger than average irrigated yield for rye, oil palm fruit, rapeseed, dates and cocoa (Table 5). The reason for this is that average crop yields were larger for these crops in administrative units with a high share of rainfed harvested crop area. For rye, for example, highest crop yields were reported for several countries in Western Europe (Monfreda et al., 2008) where the crop is almost completely rainfed. Irrigation of rye in Southern Europe, e.g. in Spain, increased rye yields in Spain but nevertheless the yields of irrigated rye in Spain were lower than the rainfed yields in the major growing areas in Western Europe.

The percentage of crop production on irrigated land depends on the irrigated fraction of the harvested crop area and on the crop yields in irrigated and rainfed agriculture. The largest percentages of irrigated crop production were computed for rice (77%), date palm (67%), cotton (61%), citrus (58%) and sugar cane (54%).

Global production losses (referring to total rainfed and irrigated production) that would occur if no irrigation water were applied were 39% for rice, 60% for date palms, 38% for cotton, 32% for citrus and 31% for sugar cane. These values are lower than the percentage of crop production on irrigated land (Table 5) because significant crop production can be achieved in many irrigation areas with green (precipitation) water alone. Potential production losses without irrigation in irrigation areas were largest for date palms (89%), pulses (77%) and sugar beets (65%) and lowest for cocoa (13%), rye (26%) and soybeans (27%).

In the group of cereals, 43% of the crop production was on irrigated land and the potential production loss without irrigation was 47% of the production in irrigation areas and 20% of total cereal production (Table 6). Without irrigation, the largest cereal production losses would occur in Northern Africa (66%) and Southern Asia (45%) while potential production losses were very low for Northern Europe (0.001%), Western Europe (1.2%), Eastern Europe (1.5%) and Middle Africa (1.6%). At the scale of the 402 spatial unit, total cereal production losses of more than 75% were computed for California and Arizona in the United States, Neuquen in Argentina, Pernambuco in Brazil, Xinjiang in China and for the countries Egypt, Saudi Arabia, Iraq, Pakistan, United Arab Emirates, Qatar and Djibouti (Fig. 8a). In contrast, there were also many spatial units where total production loss of cereals when not using irrigation was below 1%, in particular in the Eastern United States, in South America, Central Africa, Central and Northern Europe and Western Australia. The potential production losses in irrigation areas are much larger, with the largest values in all arid regions (Fig. 8b).

Virtual water content and crop water productivity

Crop water productivity and virtual water content relate crop water use to crop production and depend therefore on the specific fraction of crop biomass that can be harvested, called harvest fraction. Crops with a large harvest fraction like forage crops, fodder grasses, sugar cane, sugar beets or potatoes have low virtual water contents and large crop water productivities (compare sorghum

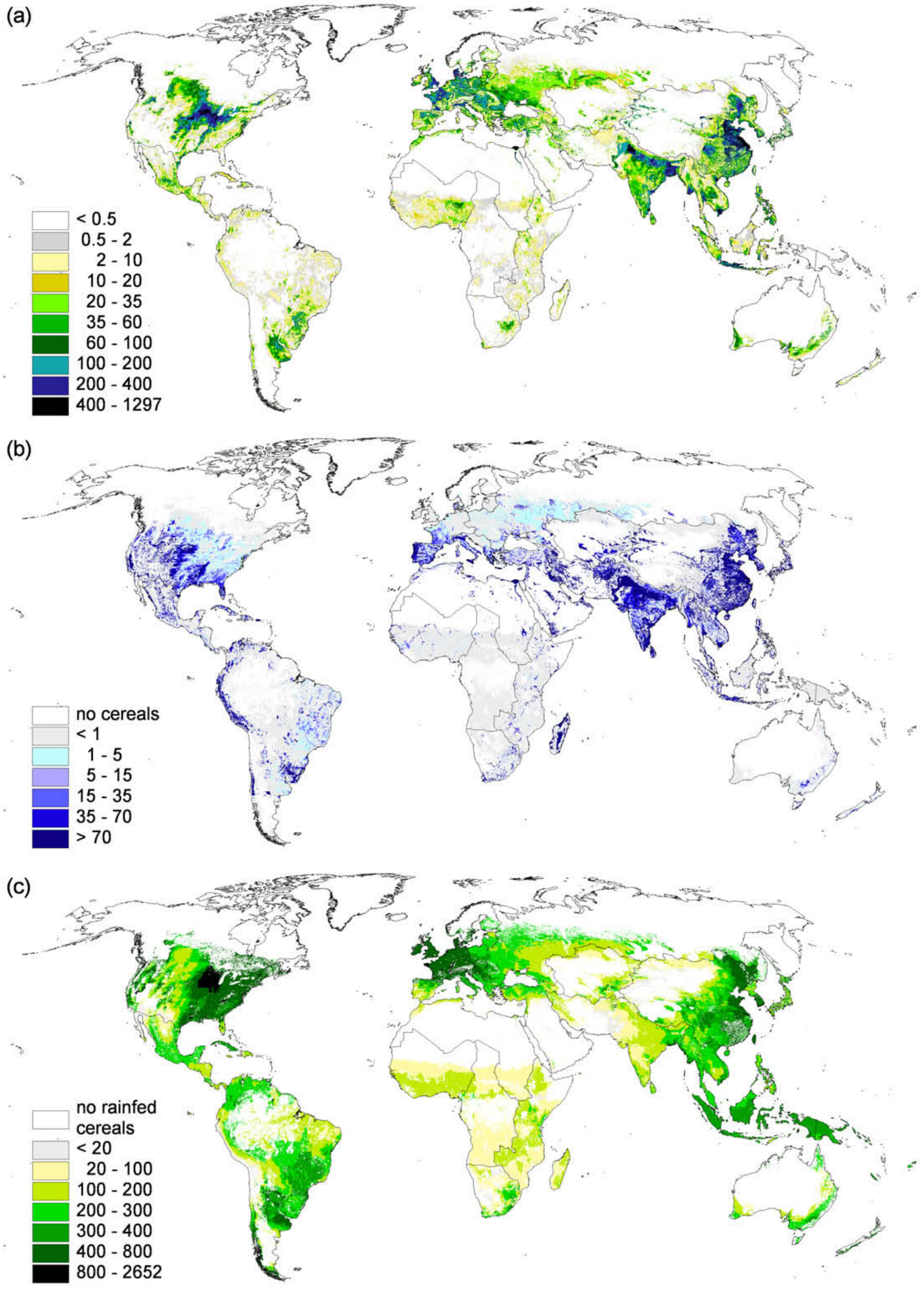

Fig. 7. Total average cereal production per total grid cell area in Mg km^{-2} yr^{-1}. (a) Percentage of cereal production from irrigated crops (b) and average yield of rainfed cereals in Mg km^{-2} (c) as computed by the global crop water model for the period 1998–2002.

used as food crop to sorghum used as forage in Table 5). In contrast, crops with a low harvest fraction like spices, cocoa or coffee have large virtual water contents and low crop water productivities. We computed the largest globally averaged crop water productivities for sugar beets (8324 g m^{-3}), sorghum if harvested as forage (6984 g m^{-3}), maize harvested as forage (5956 g m^{-3}), sugar cane (5593 g m^{-3}) and potatoes (4162 g m^{-3}) and the lowest crop water productivities for cocoa (49 g m^{-3}) and coffee (66 g m^{-3}). Among the cereals, average crop water productivity was largest for rye (1637 g m^{-3}) and lowest for millet (191 g m^{-3}). Largest contents of blue virtual water were computed for dates (2132 m^3 Mg^{-1}) and cotton seed (1475 m^3 Mg^{-1}) while cocoa, coffee, cassava and oil palm fruit contained almost only green water (Table 5).

Average crop water productivity of cereal crops was 714 g m^{-3}, while virtual water contents were 1109 m^3 Mg^{-1} of green water and 291 m^3 Mg^{-1} of blue water. Largest crop water productivities

Table 5

Total crop production (PRD_T), irrigated crop production as percentage of total crop production (PRD_I), crop yields in rainfed (Y_R) and irrigated (Y_I) agriculture, production loss when not using irrigation compared to actual production in irrigated areas (PLNI_I) and total agriculture (PLNI_T), blue (VWC_B) and green (VWC_G) virtual water content and crop water productivity (CWP) by crop class.

Crop	PRD_T ($Tg\ yr^{-1}$)	PRD_I (%)	Y_R ($Mg\ km^{-2}$)	Y_I ($Mg\ km^{-2}$)	PLNI on AEI (%)	PLNI total (%)	VWC_B ($m^3\ Mg^{-1}$)	VWC_G ($m^3\ Mg^{-1}$)	CWP ($g\ m^{-3}$)
Wheat	584	36.8	249	323	44.6	16.5	356	1113	681
Maize (grain)	604	25.7	411	568	36.1	9.3	120	969	919
Rice	681	76.6	255	506	50.7	38.8	451	931	723
Barley	136	9.8	243	287	52.7	5.3	79	1104	845
Rye (grain)	20	4.0	215	209	25.9	1.2	25	586	1637
Millet	26	8.6	74	127	30.7	2.8	153	5076	191
Sorghum (grain)	56	14.8	132	247	40.5	6.1	191	3108	303
Cereals (grain)	2108	43.5	266	442	46.7	20.3	291	1109	714
Soybeans	166	8.4	221	232	27.5	2.3	104	2302	416
Sunflower	25	9.4	117	186	58.4	5.8	163	2695	350
Potatoes	312	30.1	1366	2502	55.5	16.7	43	197	4162
Cassava	162	0.1	1051	1902	47.9	0.1	<0.5	884	1131
Sugar cane	1350	54.2	5751	7179	56.3	30.5	51	128	5593
Sugar beets	241	32.5	3520	4978	64.9	21.2	38	82	8324
Oil palm	121	<0.05	1258	365	29.1	<0.05	<0.5	964	1037
Rapeseed	37	11.4	154	123	62.5	7.2	214	1388	625
Groundnuts	33	27.0	127	243	30.3	8.3	228	2717	340
Pulses	54	18.1	71	179	76.9	14.6	415	3217	275
Citrus	109	57.5	1185	1767	55.9	32.2	212	423	1575
Date palm	5	67.0	830	454	89.3	59.8	2132	366	400
Grapes	59	31.9	741	1091	37.0	11.8	121	429	1819
Cotton	57	61.4	129	214	62.4	38.4	1475	2313	264
Cocoa	3	0.1	48	23	12.9	<0.05	10	20 363	49
Coffee	7	2.3	67	89	34.5	0.8	165	14 939	66
Others perennial	386	28.6	457	859	55.7	16.0	217	1335	644
Fodder grasses	1593	16.3	1433	2225	62.7	10.2	57	362	2390
Others annual	1047	29.1	837	1515	61.5	17.9	59	329	2579
Maize (forage)	383	22.3	2428	3312	47.0	10.5	28	140	5956
Rye (forage)	31	3.7	3325	2067	46.7	1.8	16	836	1173
Sorghum (forage)	23	14.3	2085	3000	41.7	6.0	17	126	6984
Total	8312	33.0	561	879	54.0	17.8	142	662	1243

of cereals were computed for Western Europe (1603 $g\ m^{-3}$), Northern Europe (1598 $g\ m^{-3}$), Eastern Asia (1193 $g\ m^{-3}$), Southern Europe (1109 $g\ m^{-3}$) and Northern America (1058 $g\ m^{-3}$), while crop water productivities were in particular low for all regions in Africa, except of Southern Africa. On a continental scale crop water productivity in Europe (including Russia) was about three times larger than in Africa, which was mainly caused by different average cereals yields of 340 $Mg\ km^{-2}$ in Europe and 129 $Mg\ km^{-2}$ in Africa while the average evapotranspiration during the cropping season was more similar (443 mm in Africa and 367 mm in Europe). The fraction of blue virtual water content was largest in Asia and lowest in Oceania (Table 6).

Total crop water use (evapotranspiration), virtual water content and percentage of blue virtual water content for wheat are shown in Fig. 9. Total crop water use was largest in the main wheat growing regions in Northern India and Pakistan, in the Great Plains region in Northern America, in the North China Plain, in North East Argentina, in a belt through Europe and Southern Russia ranging from about 40° N to 57° N, in Turkey and in the Euphrates-Tigris region (Fig. 9a). Virtual water contents below 750 $m^3\ Mg^{-1}$ were computed for wheat growing areas in Western and Northern Europe, in Northern China, in the North-West of the United States, in the northern wheat growing areas in Canada and some minor growing areas in Africa. The largest virtual water contents were computed for the minor growing areas in tropical regions (Fig. 9b). Extended areas where more than 50% of the virtual water content was blue are found in Northern China, Southern Asia, Mexico and in very arid wheat growing regions, in particular in Northern Africa and the Near East region. In all the other areas virtual water content of wheat was predominantly green (Fig. 9c).

Discussion

We discuss in the following the main limitations and uncertainties of GCWM (Section "Limitations and uncertainties"). Then, we compare GCWM results to results of other models and to census-based statistical information (Section "Model Validation"). Finally, some future model improvements are discussed (Section "Future improvements of GCWM").

Limitations and uncertainties

Limitations and uncertainties of GCWM are due to input data, the program algorithms and parameters and other modeling assumptions. For example, the parameters and methods used to define daily crop coefficients (Table 1) or crop yield (Table 2) should be considered as a strong simplification of reality. The variability of growing characteristics between different crops but also between varieties of the same crop is large and cannot be represented in the model. In the following, we discuss the most important model limitations and sources of uncertainty. We need to point out that there are other uncertainties and limitations (e.g. missing consideration of interception, limitation of the model to cropland) that are not discussed in detail.

Input data

The input data used by GCWM introduced several uncertainties. Time series of climate data were not available at the required spatial resolution of 5′ and the required temporal resolution of 1 day, and had to be roughly estimated from lower resolution climate data. These basic climate data (with resolutions of 0.5° or 10′),

Table 6
Cereals: total crop production (PRD_T), irrigated crop production as percentage of total crop production (PRD_I), crop yields in rainfed (Y_R) and irrigated (Y_I) agriculture, production loss when not using irrigation compared to actual production in irrigated areas (PLNI_I) and total agriculture (PLNI_T), blue (VWC_B) and green (VWC_G) virtual water content and crop water productivity (CWP), per continent and region.

Crop	PRD_T ($Tg\ yr^{-1}$)	PRD_I (%)	Y_R ($Mg\ km^{-2}$)	Y_I ($Mg\ km^{-2}$)	PLNI on AEI (%)	PLNI total (%)	VWC_B ($m^3\ Mg^{-1}$)	VWC_G ($m^3\ Mg^{-1}$)	CWP ($g\ m^{-3}$)
Eastern Africa	22	16.8	126	221	51.6	8.7	203	2772	336
Middle Africa	4	3.0	82	206	53.9	1.6	56	4664	212
Northern Africa	31	68.9	69	540	95.6	66.0	859	1604	406
Southern Africa	11	11.9	215	335	42.6	5.1	112	1521	612
Western Africa	32	3.1	94	272	75.8	2.3	65	5044	196
Africa	100	27.6	102	428	86.5	23.9	349	3083	291
Caribbean	2	49.3	152	314	38.5	18.9	306	2188	401
Central America	32	34.1	228	320	37.7	12.9	292	1788	481
Northern America	383	17.0	472	844	54.3	9.2	116	830	1058
South America	101	15.9	289	463	48.3	7.7	98	1564	601
America	518	17.9	398	625	51.2	9.2	124	1038	861
Central Asia	21	30.6	114	282	47.5	14.9	288	1537	548
Eastern Asia	545	78.2	389	549	35.1	27.5	237	601	1193
South-Eastern Asia	169	50.2	272	419	38.8	19.5	246	1452	589
Southern Asia	326	70.4	150	305	64.0	45.1	915	1268	458
Western Asia	42	34.7	179	283	61.9	21.6	554	1342	527
Asia	1104	69.0	221	422	44.9	31.0	452	975	701
Eastern Europe	151	4.0	226	303	36.3	1.5	32	1553	631
Northern Europe	42	1.8	527	625	0.1	<0.05	<0.5	626	1598
Southern Europe	58	33.3	306	865	49.3	16.4	145	757	1109
Western Europe	102	5.5	670	942	21.8	1.2	13	611	1603
Europe + Russia	353	8.9	325	643	40.8	3.7	41	1039	926
Oceania	33	6.5	190	623	65.0	4.2	44	1467	662
World	2108	43.5	266	442	46.7	20.3	291	1109	714

which were developed by interpolation of station data, are by themselves expected to be rather uncertain outside regions with a high station density, i.e. outside Europe and the Eastern USA (Mitchell and Jones, 2005; New et al., 2002).

Soil water capacity is based on the identification of 4931 map units with one dominant soil and up to seven component soils, and the linkage to soil properties derived from 10,089 soil profiles by pedotransfer rules (Batjes, 2006). While the relative extent of dominant soil and component soils are available for each map unit, these areal fractions are not known at the grid cell level. Additionally, land use is often very selective with cropland on the better soils (with higher soil water capacities) and forest or natural vegetation on the less suitable soils (with lower soil water capacities). The specific properties of the soil beneath cropland are therefore uncertain, in particular in complex map units.

The data set MIRCA2000, which is used to define growing areas and cropping periods of irrigated and rainfed crops, was developed by combining spatial data layers of harvested crop area (Monfreda et al., 2008), cropland extent (Ramankutty et al., 2008) and area equipped for irrigation (Siebert et al., 2006), with cropping calendars and statistics of irrigated harvested crop area that were derived from several data bases and from the literature (Portmann et al., submitted for publication). While Monfreda et al. (2008) used crop statistics for up to about 22,000 spatial units (depending on the crop type) to define harvested crop areas and crop yields per grid cell, Portmann et al. (submitted for publication) used irrigation statistics and crop calendars for 402 spatial units to subdivide these harvested areas further into harvested areas of irrigated and rainfed crops. Several assumptions and expert guesses were required because irrigation statistics and crop calendars were in many cases only available for the major crops. The estimates of irrigated and rainfed harvested areas and related cropping periods are therefore necessarily more uncertain than total harvested crop area, in particular at the grid cell level. In general, minor growing areas are captured less precisely in MIRCA2000, and a low spatial resolution of the statistical input data has caused some artifacts in the crop pattern. For example, in several countries of Sub-Saharan Africa where wheat was assumed to be rainfed (e.g. Nigeria, Angola, Botswana and Mozambique), there are harvested areas for wheat in almost every grid cell, albeit with a very low value (compare Fig. 9a and b). This pattern was introduced into MIRCA2000 by the basic spatial statistical units used to generate the harvested areas (Monfreda et al., 2008). In countries, where wheat was assumed to be irrigated (e.g. Mali, Burkina Faso, Namibia, Zimbabwe, and Zambia), wheat growing areas are in contrast concentrated in the few grid cells that contain irrigation areas (Fig. 9c).

Method to compute reference crop evapotranspiration

The method to compute reference evapotranspiration ET_0 has a large impact on the results of this study because ET_0 is used to simulate both crop water uses and crop yields of rainfed and irrigated crops. To test the sensitivity of the modeling results to changes in ET_0, we computed crop water uses, crop yields and potential production losses without irrigation by calculating ET_0 not only according to the FAO Penman–Monteith equation (Eq. (4), called PM in the following) but also according to Priestley–Taylor (Priestley and Taylor, 1972, Eq. (5)), modified according to Shuttleworth (1993) (called PT_SW in the following). In a third alternative, we set the parameter α in the Priestley–Taylor equation (Eq. (5)) to 1.32 (instead of 1.26 in humid and 1.74 in semi-arid areas in PT-SW), similar to what is done in the global vegetation model LPJmL (Rost et al., 2008; Bondeau et al., 2007). This run is called

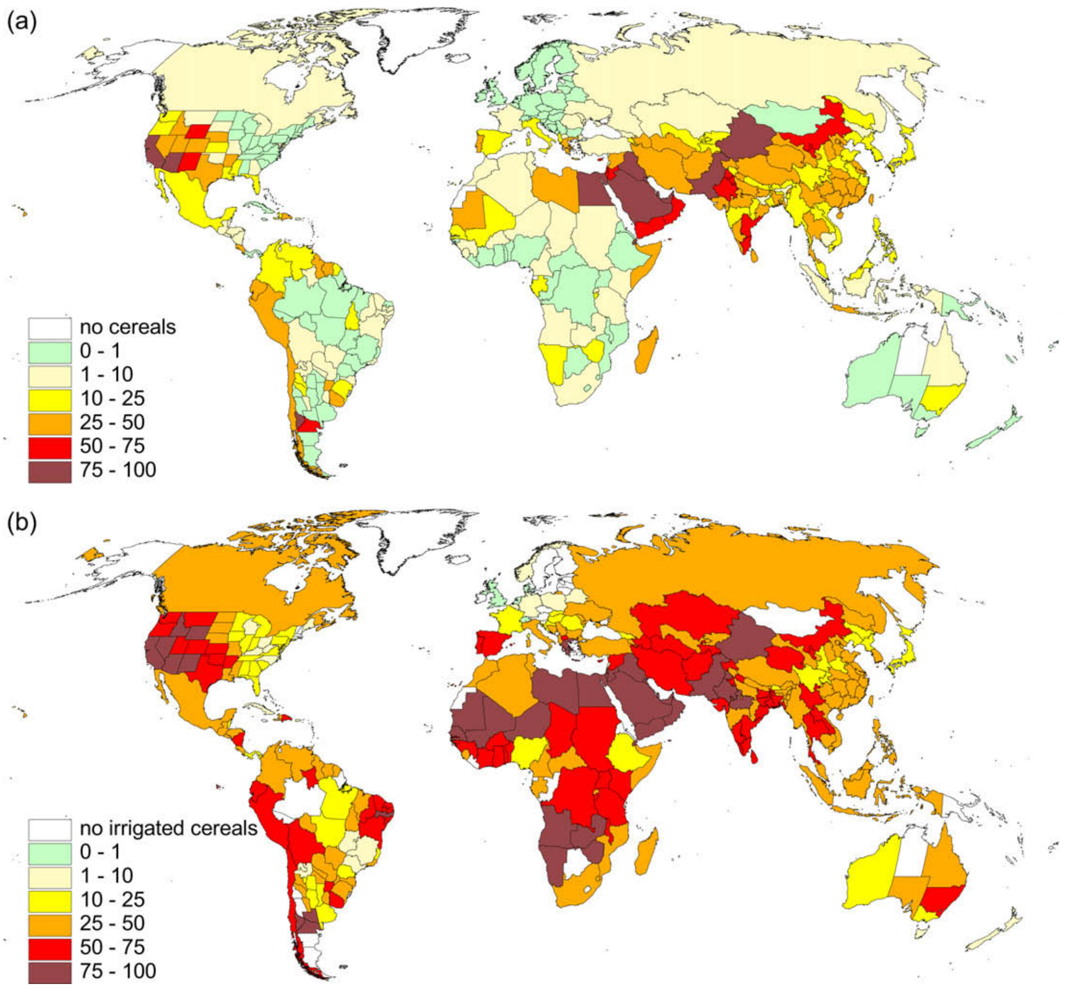

Fig. 8. Loss in total cereal production (a) and in irrigated cereals production (b) if no irrigation water was applied compared to actual cereal production computed by the global crop water model for the period 1998–2002.

PT_LPJ in the following. We found that green crop water use of rainfed crops increased by about 1%, and green crop water use of irrigated crops increased by 4% when switching from Penman–Monteith to Priestley–Taylor (Table 7). Blue crop water use increased by 23%, from 1180 $km^3\ yr^{-1}$ to 1448 $km^3\ yr^{-1}$, when using PT_SW and decreased by about 3% to 1145 $km^3\ yr^{-1}$ when using PT_LPJ. Effects in similar magnitude are found if only the group of cereals is considered (Table 7). The significant differences in blue water use and the relatively small differences in green water use can be explained by the fact that green water use is limited by available soil moisture, while blue water use was computed as the difference of *PET* to *AET* (see Section "Modeling of crop-specific blue and green consumptive water uses"). Therefore, changes in *PET* affect blue water uses much more than green water uses. The differences in blue water use between PT_SW and PT_LPJ are caused by the setting of the scaling parameter α for semi-arid climate, with $\alpha = 1.74$ in PT_SW and $\alpha = 1.32$ in PT_LPJ. Shuttleworth (1993) derived the large alpha-value of 1.74 for irrigated fields in the Western USA, which showed a high evapotranspiration due to the influence of the surrounding dry area.

The method to compute reference crop evapotranspiration only had a small impact on simulated rainfed and irrigated yields of cereals and PLNI (Table 7). At the regional scale largest differences in PLNI were computed for Southern Asia, where PLNI of cereals was 45% for PM and 50% for PT_SW, and for Southern Europe where PLNI of cereals was 16% for PM and 19% for PT_SW. In the other regions both computed PLNI values were very similar.

Grouping of crops

Limited availability of input data made it necessary to group several specific crops into the crop classes pulses, citrus, fodder grasses, others perennial and others annual. While the share of specific crops within these groups varies from country to country and grid cell to grid cell, only one constant parameter set was used for each of these crop groups to compute crop water uses, crop yields and crop water productivity (Tables 1 and 2). Results presented for groups of crops are therefore much more uncertain than results presented for specific crops (Tables 3 and 5). Additionally, in case of crop groups, average crop yields and total crop production, as well as the derived variables PLNI, VWC and CWP are dominated by crops with the largest yields, while the contribution of crops with very low yields (e.g. spices in the crop groups others annual or others perennial) is very low.

Rice

The simulation of water use and yield of rice in GCWM only partially accounts for the specific conditions in paddy rice cultivation. To account for the sensitivity of paddy rice to missing soil moisture, the parameter p_{std} was set to 0 (Table 1), which means that crop water requirements in rainfed paddy cultivation must be fulfilled by precipitation or irrigation each day during the growing season to avoid yield losses. However, water uses, runoff, deep percolation and crop yield depend also on site specific soil and water management, which could not be represented in this global study. It is well known that the yields for rainfed rice differ between up-

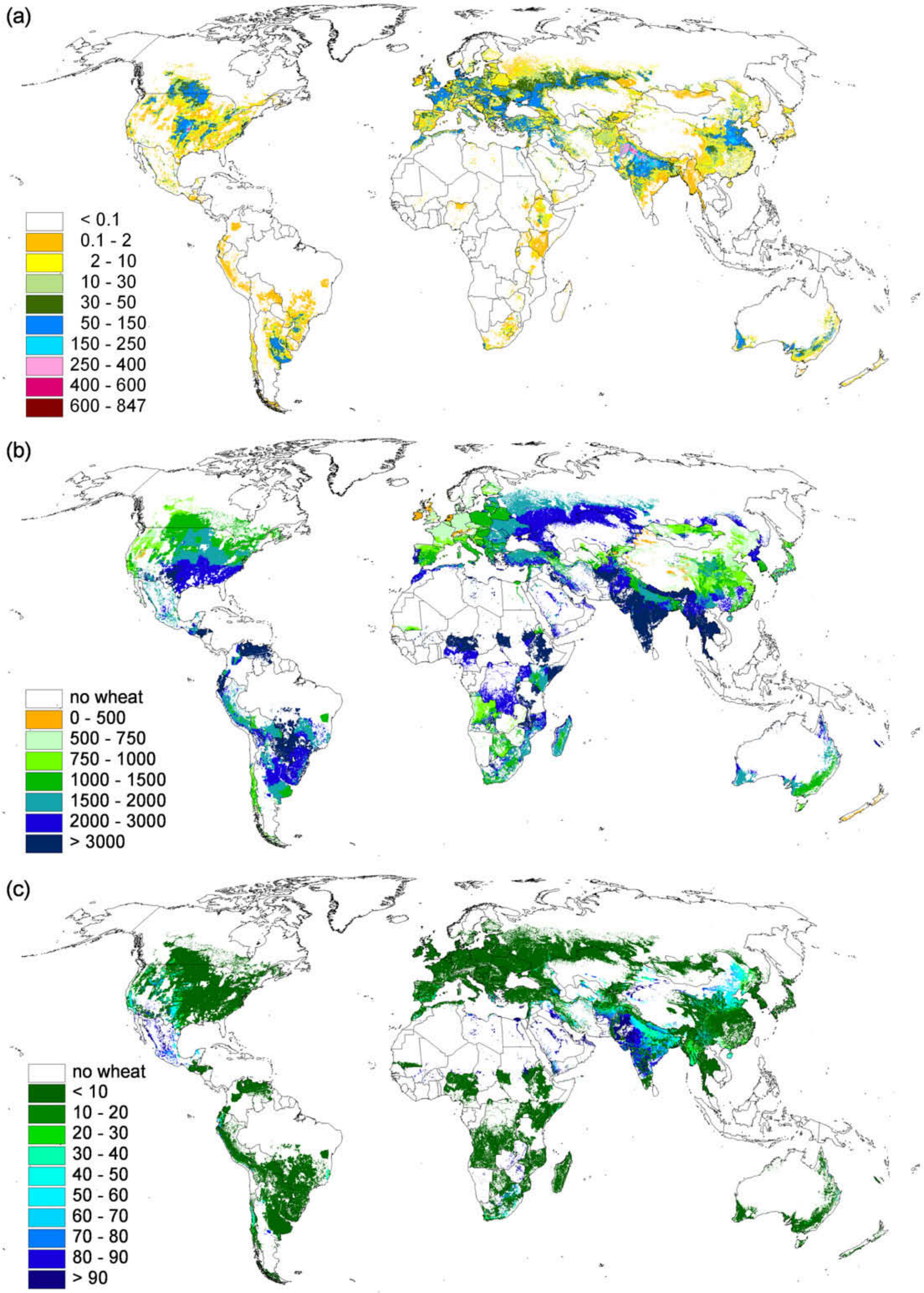

Fig. 9. Total crop water use of wheat related to total grid cell area in mm yr^{-1} (a) total virtual water content of wheat in m^3 Mg^{-1} (b) and percentage of blue virtual water content of wheat (c) computed by the global crop water model for the period 1998–2002.

land and lowland rice. For example, average yields for rice in Africa during the period 1999–2003 were 1.0 t ha^{-1} for upland rice, 2.0 t ha^{-1} for rainfed lowland rice and 3.4 t ha^{-1} for irrigated lowland rice (Somado et al., 2008). While the fractions of the different rice systems are known for many countries (IRRI, 2008) their spatial distribution is not known at the global scale. Therefore, we could not distinguish rainfed rice yields in GCWM with respect to the specific rice system.

Rooting depth

The rooting depth of irrigated and rainfed crops was defined based on crop characteristics but neglects that the effective rooting depth is often also limited by the soil. For example, soil water capacity maybe overestimated if computing soil water balances in GCWM, in particular for rainfed crops that have a large potential rooting depth like millet, sorghum, sugar cane, date palms and grapes. This could result in an underestimation of crop water stress

Table 7
Comparison of crop water uses, yields in irrigated and rainfed cereal production and cereals production loss when not using irrigation computed by the global crop water model using the Penman–Monteith method (PM) or the Priestley–Taylor method (PT_SW, PT_LPJ) to calculate the Reference Evapotranspiration. The difference between PT_SW and PT_LPJ is the scaling coefficient α set to 1.32 in PT_LPJ and to 1.74 for arid land and 1.28 for humid land in PT_SW.

Variable	PM	PT_SW	PT_LPJ
Blue crop water use (km^3 yr^{-1})	1180	1448	1145
Green crop water use of irrigated crops (km^3 yr^{-1})	919	959	951
Green crop water use of rainfed crops (km^3 yr^{-1})	4586	4772	4707
Total crop water use (km^3 yr^{-1})	6685	7178	6803
Blue crop water use of cereals (km^3 yr^{-1})	614	770	619
Green crop water use of irrigated cereals (km^3 yr^{-1})	568	599	595
Green crop water use of rainfed cereals (km^3 yr^{-1})	1769	1859	1806
Total crop water use of cereals (km^3 yr^{-1})	2950	3228	3020
Average yield of irrigated cereals (Mg km^{-2})	442	447	n.a.
Average yield of rainfed cereals (Mg km^{-2})	266	264	n.a.
Total cereals production loss when not using irrigation (%)	20.3	21.6	n.a.

during short dry spells, and thus, for irrigated crops, in an underestimation of blue water use.

Optimal versus actual water use in irrigated agriculture

The method to compute water use of irrigated crops in GCWM assumes that irrigation is used to allow the crop to evapotranspirate at its potential, not-water-limited rate so that optimal plant growth is ensured. Therefore, we assumed that irrigated crops never suffer any yield reduction due to water stress. In reality, however, irrigation water application may be less than optimal because of water scarcity or failure of the water supply system. Besides, farmers who pump irrigated water may decide to irrigate less than optimal and to accept moderate yield losses to save costs for energy or labor and to maximize the economic benefit. Therefore, blue consumptive water uses in irrigated agriculture maybe lower than the requirement computed by GCWM. It is, however, very difficult to prove this hypothesis because statistics of irrigation water use refer in almost all cases to water withdrawals and not to consumptive water uses. Water withdrawals are larger than consumptive uses because they include evaporation from open water e.g. in irrigation canals and return flows to surface and groundwater. Conversion of consumptive uses to withdrawal uses requires knowledge of the so-called irrigation efficiency, which is also scale-dependent because losses in the upstream area maybe recycled in downstream irrigation areas. In this study, we therefore only report consumptive uses, also because of the fact that there is no equivalent for blue water withdrawals in green water use.

Method to compute potential production losses without irrigation

The method to compute production losses when not using irrigation quantifies the reduction of crop production that would occur when using only green water. It does not consider that without irrigation crop yields may decrease below a certain limit so that crop production is economically not attractive anymore for the farmers. Therefore, the computed production losses should be considered as a conservative minimum.

Model validation

Only very few models compute water uses and yields for specific irrigated and rainfed crops at the global scale. Since the growing areas of irrigated and rainfed crops were very different in these models as compared to the MIRCA2000 growing areas used in this study, the comparability of GCWM model output to output of these models is limited. Blue water consumptive use computed by H07 (Hanasaki, personal communication) was 1320 km^3 yr^{-1} (average 1986–1995), while in case of LPJmL (Rost et al., 2008) it was 1364 km^3 yr^{-1} (average 1971–2000) and in the case of WATERSIM (De Fraiture, 2007) it was 1450 km^3 yr^{-1} for year 2000. In comparison, blue water consumptive use as computed by GCWM was between 1150 km^3 yr^{-1} and 1450 km^3 yr^{-1}, for the time period 1998–2002, depending on the method used to compute ET_0 (Table 7). Green water use on cropland could not be compared to outputs of these models because results are highly dependent on the specific cropland extent considered in the calculations, in particular whether fallow land has been included. This information was not available for the three studies mentioned above.

Comparison to independent estimates of irrigation water withdrawals and consumptive use

A comparison of blue water use computed by GCWM to census-based information on irrigation water withdrawals per country in Europe (EUROSTAT, 2007), irrigation consumptive use in the United States of America (Hutson et al., 2004; Solley et al., 1998) and simulation results of FAO for developing countries (FAO, 2005) generally found a good agreement (Siebert and Döll, 2008). Simulation results for the USA fit better to the reported consumptive water uses per federal state when using PT_SW to compute ET_0 (r^2 of 0.94, Nash–Sutcliffe coefficient 0.93) instead of using PT_LPJ (r^2 of 0.90, Nash–Sutcliffe coefficient 0.88) or PM (r^2 of 0.85, Nash–Sutcliffe coefficient 0.82). This may be related to the fact that PT_SW was developed in the USA and applied to estimate consumptive uses there. The total net irrigation water requirement (consumptive use) of the 90 developing countries computed by FAO was 824 km^3 yr^{-1}, while the corresponding CWU_B of GCWM was 902 km^3 yr^{-1} when using PM, 911 km^3 yr^{-1} when using PT_LPJ and 1148 km^3 yr^{-1} when using PT_SW. The better correspondence might be related to the fact that FAO also uses PM to compute reference crop evapotranspiration. It was found, however, that the irrigation water requirements simulated by GCWM were in general larger than FAO values for many arid countries, which might be explained by the use of different land use information. CWU_B computed using PT_SW even exceeded reported agricultural withdrawal water uses for several countries (e.g. in Algeria, Chad, Jordan, Lebanon, Pakistan, South Africa, and Tunisia) while results using PM were much lower and thus more realistic for these countries. For countries, in which rice is the dominating irrigated crop, FAO computed larger values (e.g. for Indonesia, Vietnam, Myanmar, and Philippines). The reason may be that for rice cultivation the FAO model adds to the computed consumptive water use (crop evapotranspiration) an additional 250 mm of water at the beginning of the growing season to flood the paddy fields (FAO, 2005).

This comparison shows that it is not possible to clearly favor one method to compute reference crop evapotranspiration. Due to the apparent overestimation of blue crop water use in semi-arid areas outside the USA with the PT_SW method, the PM method was chosen as the standard method.

Comparison to estimates included in the water footprint of nations (Arjen Hoekstra and colleagues)

Total crop production (PRD), total crop water use (CWU_T) and total virtual water content (VWC) were compared, for the 21 specific crops considered in GCWM and the group of cereals, to annual averages computed for the period 1997–2001 by Hoekstra and Chapagain (2008) to quantify the water footprint of nations (Table 8). Differences in PRD were less than 10% for all the crops except rice. Rice production in GCWM (681 Tg yr^{-1}) was about 11% larger. The reason was that the harvested crop area in the MIRCA2000 data set used as input in GCWM exceeded the harvested area assumed by Hoekstra and Chapagain (2008) (hereafter abbreviated as HC) by a similar amount. The difference was in particular large for China, where MIRCA2000 assumed an irrigated harvested rice

Table 8
Comparison of crop production (PRD), total crop water use (CWU_T) and virtual water content (VWC) as computed for the Water Footprint of Nations database for the period 1997–2001 (WFPN, Hoekstra and Chapagain, 2008) and by the global crop water model for the period 1998–2002 (GCWM).

Crop	PRD (Tg yr^{-1})		CWU_T (km^3 yr^{-1})		VWC (m^3 Mg^{-1})	
	WFPN	GCWM	WFPN	GCWM	WFPN	GCWM
Wheat	595	584	793	858	1334	1469
Maize (grain)	603	604	548	658	909	1088
Rice	593	681	1359	941	2291	1383
Barley	140	136	194	161	1388	1183
Rye (grain)	22	20	20	12	901	611
Millet	28	26	129	135	4596	5229
Sorghum (grain)	59	56	170	183	2853	3300
Cereals (grain)	2040	2108	3212	2950	1575	1400
Soybeans	160	166	286	399	1789	2406
Sunflower	25	25	76	72	3069	2858
Potatoes	309	312	79	75	255	240
Cassava	172	162	104	144	605	884
Sugar cane	1258	1350	220	241	175	179
Sugar beets	253	241	29	29	113	120
Oil palm fruit	112	121	117	117	1053	964
Rapeseed	38	37	61	59	1611	1601
Groundnuts	33	33	104	98	3145	2945
Dates	6	5	17	12	3030	2498
Grapes	61	59	40	32	655	550
Cotton	55	57	199	215	3644	3788
Cocoa	3	3	86	66	27 218	20 373
Coffee	7	7	119	103	17 373	15 104

area of 385,000 km^2 yr^{-1} based on the statistics reported in FAO (2005) while other data bases like FAOSTAT (http://faostat.fao.org) report a total harvested rice area between 291,000 km^2 yr^{-1} and 321,000 km^2 yr^{-1} for the period 1997–2001. Despite of the larger harvested rice area, CWU_T for rice was much lower in GCWM (941 km^3 yr^{-1}) than the HC value of 1359 km^3 yr^{-1}. The reason of this difference is probably that the authors assumed an additional water use of 300 mm of water (for percolation) during the plantation period of the rice crops. Consequently, VWC of rice is 66% larger in HC than in GCWM. In a study of the virtual water footprint of rice (Mom, 2007), such a percolation loss was not assumed, and the computed global average virtual water content, for rice, of 1007 m^3 Mg^{-1} of green water and 448 m^3 Mg^{-1} of blue water is very similar to the VWC of 931 m^3 Mg^{-1} (green) and 451 m^3 Mg^{-1} (blue) as computed by GCWM. Total crop water use CWU_T computed in GCWM for all the other crops compared reasonably to well to the water uses computed by HC. CWU_T computed by GCWM is more than 10% larger for wheat, maize, soybeans, and cassava and more than 10% smaller for barley, rye, dates, grapes and cocoa. Differences of less than 10% for all three variables (PRD, CWU_T and VWC) are found for sunflower, potatoes, sugar cane, sugar beets, rapeseed, groundnuts, cotton and coffee (Table 8). The agreement between CWU_T of HC and this study is very surprising because Hoekstra and Chapagain (2008) assumed that crop evapotranspiration was not restricted by water stress, not only in the case of irrigated crops but also in the case of rainfed crops. Thus, the HC value should be much larger than the value of this study, because low soil moisture in arid and semi-arid regions resulted in significantly decreased evapotranspiration of rainfed crops as compared to irrigated crops. A comparison at the country scale between HC and this study showed, that crop evapotranspiration was much larger in HC in most arid countries and in countries where a large part of the harvested area was used for paddy rice cultivation. In contrast, crop evapotranspiration was much lower in HC for most countries in temperate climate so that differences for CWU_T leveled out at the global scale. However, due to trade flows from mainly temperate regions to arid and semi-arid regions, significant differences are expected when using CWU_T from this study instead of crop evapotranspiration from HC for the computation of virtual water trade.

Comparison to irrigated and rainfeld yields in developing countries (FAO)

Production from irrigated land is not only enhanced by increased water availability but also elevated by increased nutrient inputs associated with irrigation. The effect of nutrient input was implicitly included in our model, since the estimated ratio of rainfed to irrigated yield as a function of the ratio of *AET* to *PET* used selected statistical yield data (see Section "Modeling of irrigated and rainfed crop productions and potential production losses without irrigation"). We might suspect that global production gain was overestimated because most of the yield data used to establish the relation between yield ratios and ET-ratios were from the US where sufficient nutrient supply can be assumed. Therefore, we compared irrigated and rainfed crop production and yields to data reported by FAO for the group of 93 developing countries for the crops wheat, rice, maize and the group of cereals (Table 9). We found a very good agreement of the share of irrigated crop production in total crop production, while the average area weighted yield was in most cases about 10% larger in GCWM for both irrigated and rainfed crops.

Since average yields were not computed in GCWM but were a model input from Monfreda et al., 2008, yield data used by FAO apparently differ from those compiled by Monfreda et al. (2008). The ratio of average rainfed crop yield to average irrigated crop yield computed by GCWM was similar to the FAO estimates for the crops wheat and rice and for the groups of cereals. For maize, FAO computed a ratio of average rainfed yields to average irrigated yields of 0.62 while this ratio was 0.69 in GCWM. The good agreement of the share in maize production between FAO and GCWM indicates that there are likely differences in the data used by FAO and GCWM on the share of irrigated and rainfed harvested areas for maize. Given the uncertainties in input data and parameterization, the agreement between the FAO estimates and GCWM is surprisingly good. It shows that the GCWM method to downscale irrigated and rainfed crop yields produces reasonable results for

Table 9
Share of irrigated and rainfed production and average weighted cereal yields for 93 developing countries reported by FAO (Bruinsma, 2003) for the period 1997–1999 and simulated by the global crop water model (GCWM) for the period 1998–2002.

		Share in production (%)		Average weighted yield (Mg km^{-2})	
		FAO	GCWM	FAO	GCWM
Wheat	Total			253	272
	Irrigated	65	70	311	318
	Rainfed	35	30	186	204
Rice	Total			357	406
	Irrigated	76	76	445	501
	Rainfed	24	24	220	255
Maize	Total			278	300
	Irrigated	32	33	452	436
	Rainfed	68	67	234	259
Cereals	Total			261	296
	Irrigated	59	62	393	421
	Rainfed	41	38	176	201

developing countries even though mainly data from the USA were used for downscaling.

Comparison to independent data on crop water productivity

Crop water productivity (CWP) computed for wheat, maize and rice was compared to independent data from field studies assembled and reported by Zwart and Bastiaanssen (2004), hereafter abbreviated as ZB. The authors obtained data for CWP published in the literature accounting for results of experiments not older than 25 years and considered only data that were based on measured crop evapotranspiration, excluding data based on simulated or computed crop evapotranspiration. 412 records from 28 publications were available for wheat, 105 records from 13 studies for rice and 233 records from 26 studies for maize. We compared the minimum, maximum, mean and median values of CWP reported for the three crops to area weighted averages of CWP computed by GCWM for the 402 spatial units. To define the range of CWP in GCWM we only considered spatial units with harvested crop areas of more than 10 km^2 yr^{-1}. This resulted in 240 records for wheat, 210 records for rice and 283 records for maize.

We found that the total range of CWP computed by GCWM was larger than the range reported in ZB while the median and mean of CWP computed by GCWM were lower than the corresponding values in ZB. The range of CWP for wheat computed by GCWM was 0.09–2.98 kg m^{-3} while ZB reported a range of 0.11–2.67 kg m^{-3}. We computed an area weighted global average CWP of 0.68 kg m^{-3} (Table 5) while ZB determined, from the field studies considered, a mean CWP of 1.09 kg m^{-3} and a median of 1.02 kg m^{-3}, respectively. The findings of the comparison for rice and maize were very similar. The CWP range was larger in GCWM and average CWP computed by GCWM was only 58% (maize) or 70% (rice) of the median given in ZB.

It is difficult to identify the reasons for the differences in CWP because ZB did not report the corresponding yield and crop evapotranspiration values of the field experiments. In GCWM very low or very high values for CWP were due to very low or very high yields. The lowest CWP of wheat was computed for Venezuela where the corresponding crop yield was only 40 Mg km^{-2} while the largest CWP of wheat was calculated for Ireland where wheat yield was 853 Mg km^{-2}. While these yields are confirmed also by other data bases like FAOSTAT (http://faostat.fao.org/default.aspx), crop evapotranspiration simulated by GCWM is likely to be more uncertain. In several countries where we computed very large CWP of wheat (like Ireland, UK and the Netherlands) we may underestimate crop evapotranspiration because the crop coefficients used in this global analysis (see Eq. (6), Table 1) did not reflect the frequent occurrence of rainfall events in these countries. On the other hand we may overestimate crop evapotranspiration in several semi-arid countries where we computed very low CWP because of the high rooting depth in rainfed agriculture (discussed in Section “Rooting depth”). Another reason might be that the density of plants on fields in many developing countries is rather low. Combined to an extensive weed control this could result in a reduced evapotranspiration.

Among the 15 spatial units where we computed the largest CWP for wheat there were nine European countries, four provinces in North China, one federal state of the US and New Zealand. ZB also found large CWP in North China. Fourteen of the 28 studies on CWP of wheat considered by ZB were undertaken in India and China but unfortunately there was no record for a European location in their data base. The 15 spatial units where we computed the lowest CWP of wheat were located in tropical or sub-tropical climate (five African countries, four federal states in South India, three countries in tropical South America, one province in Argentina, Iraq and Thailand). Records for these regions were not available in the data used by ZB. This indicates that the specific conditions on the research sites that produced the data used by ZB may not be representative for the full range of specific site conditions in global agriculture. Therefore, average global CWP may well be lower than the mean and median values reported in ZB.

Future improvements of GCWM

A possible improvement of GCWM could be to restrict the effective rooting depth of crops by actual soil depth. A recently published new dataset provides this information for Eurasia (FAO/IIASA/ISRIC/ISSCAS/JRC, 2008), and for the other regions the information could be obtained from Batjes (2005). These data could be used to improve the estimate of total available soil water capacity within the effective root zone (Eq. (3)). The limited resolution (and quality) of the climate input is a major reason for model output uncertainty. Therefore, model runs with different climate input of higher spatial resolution (e.g. Hijmans et al., 2005) or higher temporal resolution (e.g. Hirabayashi et al., 2008) should be performed to explore the sensitivity of model results to changing climate input. The statistical data used in GCWM to compute irrigated and rainfed crop yields refer mainly to federal states of the US and for several crops no data at all have been available. A major improvement of the yield calculation may be achieved if more data on irrigated versus rainfed crop yields originating from various countries become available. The uncertainties and limitations of GCWM call for a systematic comparison of model results to results of other recently developed global models like H07 (Hanasaki et al., 2008), LPJmL (Rost et al., 2008) or WATERSIM (De Fraiture, 2007), in order to quantify the major differences and to find the reasons for the differences. Then, uncertainties could be characterized better, and further improvements could be suggested.

Conclusions

A global crop water model (GCWM) was developed that computes blue and green consumptive water uses and virtual water contents of 26 irrigated and rainfed crop classes at a spatial resolution of 5′ by 5′, taking into account multi-cropping. To downscale statistical information on average (i.e. not distinguishing between irrigated and rainfed conditions) crop yields to irrigated and rainfed crop yields we established crop-specific relationships between the ratio of rainfed crop yields and irrigated crop yields as derived from census-based statistics and the ratio of water-limited actual crop evapotranspiration and potential crop evapotranspiration. The methodology allowed also the computation of crop water productivities and the production loss that would occur without irrigation. The model was applied for the period 1998–2002. GCWM is a very data driven model. A new data set of growing areas of crops and cropping seasons of irrigated and rainfed crops is applied instead of simulating cropping patterns and seasonality. Average crop yields in 402 spatial units are downscaled so that consistency to agricultural statistics on average crop yields is preserved. GCWM is therefore well suited for assessing present day conditions in crop production, for comparisons of crop water use and crop water productivity in different countries, and for determining virtual water flows induced by crop trade. Because of the uncertainties and limitations in input data, model parameterization, and model structure (see Section ‘‘Limitations and uncertainties”) we recommend using the model for global scale assessments only.

We expect that the clear distinction of blue and green virtual water contents of crops will allow an improved analysis of the impacts of humans (via food consumption patterns) on the global freshwater system. The useful concept of the water footprint of nations and individuals (Hoekstra and Chapagain, 2008), which aims at indicating human water appropriation from the consumer’s perspective, is likely to gain clarity and relevance if green and blue water uses are not mixed up any more. Is it problematic, from a water resources perspective, if people use crops produced with almost exclusively green water? Maybe it is not unless crop production leads to water pollution. Besides, the change from natural vegetation to cropland, i.e. an increased green water use, generally leads to decreased evapotranspiration and thus an increase in the blue water resource.

One major finding of this research is that at the global scale the consumptive use of blue water in crop production in less than a fifth of the total (blue and green) water use. Another major finding is that without any irrigation, global production of cereals would decrease by ‘‘only” 20%. However, irrigation accounts for more than 90% of the total consumptive use of blue water, with households, industry and livestock requiring less than 10%, and the irrigation sector is responsible for 70% of the global withdrawals (Döll, 2008). Given the increasing competition for and scarcity of blue water resources these findings of our study raise the question whether it would not be better to stop (or strongly decrease) irrigation. Then, the additionally available blue water resources could be used to supply households and industry and to support natural ecosystems, and crop yields or production in regions where consumptive use is (mainly) from green water could ‘‘easily” be increased. Such a discussion misses an important point: the spatial distribution of irrigation requirements. The benefits of using irrigation are largest in all semi-arid and arid areas (Fig. 8), and it is particularly in these regions where water is scarce and competition for water is large. Many of these semi-arid and arid areas are located in developing countries, where irrigation generally provides income to a large number of people, and alternative opportunities to generate income are very limited, in particular in rural areas. Nevertheless, to achieve a sustainable development of water-scarce areas which strongly rely on irrigation for food and income production, it is necessary to identify socio-economic strategies that allow reducing irrigation water use by increasing virtual water imports.

References

Allan, J.A., 2003. Virtual water: the water, food, and trade nexus – useful concept or misleading metaphor? Water International 28, 4–11.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Batjes, N.H., 2006. ISRIC-WISE Derived Soil Properties on a 5 by 5 arc-minutes Global Grid. Report 2006/02, ISRIC – World Soil Information, Wageningen, The Netherlands (with data set). <http://www.isric.org>.

Batjes, N.H., 2005. ISRIC-WISE Global Data Set of Derived Soil Properties on a 0.5 by 0.5 degree Grid. Report 2005/08, ISRIC – World Soil Information, Wageningen, The Netherlands (with data set). <http://www.isric.org>.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century. Global Change Biology Vol. 13 (3), 679–706. doi:10.1111/J.1365-2486.2006.01305.x.

Bruinsma, J. (Ed.), 2003. World Agriculture: Towards 2015/2030 An FAO Perspective. FAO, Earthscan publications Ltd, London.

Cai, X., Rosegrant, M., 2002. Global water demand and supply projections. Part 1: a modeling approach. Water International 27 (3), 159–169.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water Footprint of Nations, vol. 1. Main report. Value of Water Research Report Series 16, UNESCO-IHE, Delft, The Netherlands, 80 pp.

Döll, P., 2008. Wasser weltweit: Wie groß sind die weltweiten Wasserressourcen, und wie nutzt sie der Mensch? Forschung Frankfurt 3, 54–59.

Ellis, E.C., Ramankutty, N., 2008. Putting people in the map: anthropogenic biomes of the world. Frontiers in Ecology and the Environment 6, 439–447.

EUROSTAT, 2007. Annual Water Abstraction by Source and by Sector. <http://epp.eurostat.ec.europa.eu/portal/page?_pageid=1073,46870091&_dad=portal&_schema= PORTAL&p_product_code=ENV_WATQ2_1>.

FAO/IIASA/ISRIC/ISSCAS/JRC (2008). Harmonized World Soil Database (version 1.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria. <http://www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HTML/index.html>.

FAO, 2005. Review of agricultural water use per country. FAO, Rome, Italy. <http://www.fao.org/nr/water/aquastat/water_use/index.stm>.

Fraiture, C. de, 2007. Integrated water and food analysis at the global and basin level. An application of WATERSIM. Water Resources Management 21, 185–198.

Freydank, K., Siebert, S., 2008. Towards Mapping the Extent of Irrigation in the Last Century: Time Series of Irrigated Area per Country. Frankfurt Hydrology Paper 08. Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany.

Geng, S., Penning, F.W.T., Supit, I., 1986. A simple method for generating daily rainfall data. Agricultural and Forest Meteorology 36, 363–376.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., Tanaka, K., 2008. An integrated model for the assessment of global water resources – Part 1: model description and input meteorological forcing. Hydrology and Earth System Science 12, 1007–1025.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25, 1965–1978.

Hirabayashi, Y., Kanae, S., Motoya, K., Masuda, K., Döll, P., 2008. A 59-year (1948–2006) global near-surface meteorological data set for land surface models. Part I: development of daily forcing and assessment of precipitation intensity. Hydrological Research Letters 2, 36–40.

Hoekstra, A.Y., Chapagain, A.K., 2008. Globalization of Water: Sharing the Planet’s Freshwater Resources. Blackwell Publishing, Oxford, UK.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., Maupin, M.A., 2004. Estimated Use of Water in the United States in 2000. US Geological Survey Circular 1268, Reston, United States. <http://water.usgs.gov/watuse/>.

IRRI, 2008. World Rice Statistics. <http://beta.irri.org/statistics/index.php?option=com_frontpage&Itemid=1>.

Klein Goldewijk, K., Ramankutty, N., 2004. Land cover change over the last three centuries due to human activities: the availability of new global data sets. Geographical Journal 61, 335–344.

Leff, B., Ramankutty, N., Foley, J.A., 2004. Geographic distribution of major crops across the world. Global Biogeochemical Cycles 18, GB1009. doi:10.1029/2003GB002108.

Liu, J., 2009. A GIS-based tool for modelling large-scale crop-water relations. Environmental Modelling and Software 24 (3), 411–422.

Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94, 478–493.

L'vovich, M., White, G.F., 1990. Use and transformation of terrestrial water systems. In: Turner, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (Eds.), The Earth as Transformed by Human Action. Cambridge University Press, Cambridge, US, pp. 35–252.

Ministry of Agriculture and Forestry, 2006. Agricultural Statistics 30 Years (1976–2005). Ministry of Agriculture and Forestry, Vientiane, Lao PDR. <http://faorap-apcas.org/lao.html>.

Ministry of Jahad-e-Agriculture, 2008. Cultivation Database. Ministry of Jahad-e-Agriculture, Bureau of Statistics & Information Technology, Teheran, Iran. <http://www.maj.ir/English/Statistic/Default.asp?p=statistic>.

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology 25, 693–712.

Mom, R.. 2007. A High Spatial Resolution Analysis of the Water Footprint of Global Rice Consumption. Master Thesis, University of Twente, Enschede, The Netherlands, 136 pp. <http://www.waterfootprint.org/?page=files/Publications>.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet. Part 2: the geographic distribution of crop areas, yields, physiological types, and NPP in the year 2000. Global Biogeochemical Cycles 22, GB1022. doi:10.1029/2007GB002947.

New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Climate Research 21 (1), 1–25.

NOAA, 1988. Data Announcement 88-MGG-02, Digital relief of the Surface of the Earth. NOAA, National Geophysical Data Center, Boulder, Colorado.

Portmann, F., Siebert, S., Bauer, C., Döll, P., 2008. Global Dataset of Monthly Growing Areas of 26 Irrigated Crops. Frankfurt Hydrology Paper 06. Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 400 pp.

Portmann, F.T., Siebert, S., Döll, P., 2010, MIRCA2000 - Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochemical Cycles 24, GB1011, doi:10.1029/2008GB003435.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1992. Numerical Recipes in C: The Art of Scientific Computing. Cambridge University Press. 994 pp.

Priestley, C., Taylor, R., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review 100, 81–92.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet. Part 1: The geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles 22, GB1003. doi:10.1029/2007GB002952.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research 44, W09405. doi:10.1029/2007WR006331.

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L., 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. Water Resources Research 43, W03437. doi:10.1029/2006WR005486.

Siebert, S., Döll, P., 2008. The Global Crop Water Model (GCWM): Documentation and First Results for Irrigated Crops. Frankfurt Hydrology Paper 07. Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 42 pp.

Siebert, S., Hoogeveen, J., Frenken, K., 2006. Irrigation in Africa, Europe and Latin America. Update of the Digital Global Map of Irrigation Areas to Version 4. Frankfurt Hydrology Paper 05. Institute of Physical Geography, University of Frankfurt, Frankfurt am Main, Germany, 134 pp.

Shuttleworth, W.J., 1993. Evaporation. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York, pp. 4.1–4.53.

Solley, W.B., Pierce, R.R., Perlman, H.A., 1998. Estimated use of Water in the United States in 1995. US Geological Survey Circular 1200. Denver, United States. <http://water.usgs.gov/watuse/>.

Somado, E.A., Guei, R.G., Keya, S.O., (Eds.), 2008. NERICA: The New Rice for Africa – A Compendium. Africa Rice Center (WARDA), Cotonou, Benin, 210 pp. <http://www.warda.org/publications/nerica-comp/Nerica%20Compedium.pdf>.

USDA, 1999. Farm and Ranch Irrigation Survey 1998. 1997 Census of Agriculture, vol. 3, Special Studies, Part 1, United States Department of Agriculture, National Agricultural Statistics Service, Washington DC, 187 pp. <http://www.nass.usda.gov/census/census97/fris/fris97.pdf>.

Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management 69, 115–133.