Hydrol. Earth Syst. Sci. Discuss., 12, 3593–3644, 2015
www.hydrol-earth-syst-sci-discuss.net/12/3593/2015/
doi:10.5194/hessd-12-3593-2015
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Hydrology and Earth System Sciences
Open Access
Discussions

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Water savings potentials of irrigation systems: dynamic global simulation

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Received: 6 March 2015 – Accepted: 11 March 2015 – Published: 1 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Global agricultural production is heavily sustained by irrigation, but irrigation system efficiencies are often surprisingly low. However, our knowledge of irrigation efficiencies is mostly confined to rough indicative estimates for countries or regions that do not account for spatio-temporal heterogeneity due to climate and other biophysical dependencies. To allow for refined estimates of global agricultural water use, and of water saving and water productivity potentials constrained by biophysical processes and also non-trivial downstream effects, we incorporated a dynamic representation of the three major irrigation systems (surface, sprinkler, and drip) into a process-based bio- and agrosphere model, LPJmL. Based on this enhanced model we provide a gridded worldmap of dynamically retrieved irrigation efficiencies reflecting differences in system types, crop types, climatic and hydrologic conditions, and overall crop management. We find pronounced regional patterns in beneficial irrigation efficiency (a refined irrigation efficiency indicator accounting for crop-productive water consumption only), due to differences in these features, with lowest values (< 30 %) in South Asia and Sub-Saharan Africa and highest values (> 60 %) in Europe and North America. We arrive at an estimate of global irrigation water withdrawal of 2396 km^3 (2004–2009 average); irrigation water consumption is calculated to be 1212 km^3, of which 511 km^3 are non-beneficially consumed, i.e. lost through evaporation, interception, and conveyance. Replacing surface systems by sprinkler or drip systems could, on average across the world's river basins, reduce the non-beneficial consumption at river basin level by 54 and 76 %, respectively, while maintaining the current level of crop yields. Accordingly, crop water productivity would increase by 9 and 15 %, respectively, and by much more in specific regions such as in the Indus basin. This study significantly advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems. Here presented opportunities associated with irrigation improvements are

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significant and suggest that they should be considered an important means on the way to sustainable food security.

1 Introduction

A major humanitarian challenge for the 21st century is to feed a growing world population in face of climate change and sustainability boundaries (e.g. Foley et al., 2011). In addition to requiring institutional changes, global crop production is likely to have to double to meet the demand by 2050 (Tilman et al., 2011; Alexandratos and Bruinsma, 2012; Valin et al., 2014). At present, irrigation is a key component of agriculture; global cereal production would decrease by 20 % without irrigation (Siebert and Döll, 2010), and climate change and population growth will further enhance its role in future (Neumann et al., 2011; Plusquellec, 2002). In the past 50 years irrigated area roughly doubled (FAO, 2012; Siebert et al., 2015) and today about 24 % of the total harvested cropland is irrigated, producing $>$ 40 % of the global cereal yield (Portmann et al., 2010). Irrigation is the single largest global freshwater user, accounting for $\sim$ 70 % of water withdrawals and 80–90 % of water consumption (Gleick et al., 2009).

However, as the planetary boundaries for freshwater use and land use are being approached rapidly or are already exceeded, there is little potential for increasing irrigation or expanding cropland (Steffen et al., 2015; Gerten et al., 2013). Thus, production gaps must be closed by sustainable production increases and higher cropping intensities on currently harvested land by either increasing rainfed yields or optimizing the water productivity of irrigated cropping systems and ecologically sensitive transforming rainfed systems into irrigated systems (Alexandratos and Bruinsma, 2012).

Indeed, current irrigation efficiencies are often below 50 %, as much of the diverted water is lost in the conveyance system or through inefficient application to the plants. The magnitude of these losses is determined primarily by the irrigation system (e.g. sprinkler, surface, drip) but also by meteorological and other environmental

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conditions. At first glance, the often low efficiency suggests a high potential for water savings. However, only water that leaves the system without a benefit for crop growth, such as evaporation from bare soil and other non-beneficial components (e.g. weed transpiration, Fig. 1), should be considered a manageable loss (e.g., Keller and Keller, 1995). As the different water fluxes are difficult to separate empirically, non-beneficial consumption remains a poorly measured and studied element of the irrigation water balance (Gleick et al., 2011) and associated specific saving potentials are largely neglected in discussions on irrigation improvements (e.g. Perry et al., 2009; Frederiksen and Allen, 2011; Simons et al., 2015). Also, while reducing non-beneficially consumed water clearly enables local yield increases using the same amount of water (Luquet et al., 2005; Molden et al., 2010; Al-Said et al., 2012), it inevitably reduces return flows as well. This can have mid-term negative effects on crop production through faster soil water depletion or less available water for downstream users (Ward and Pulido-Velazquez, 2008). The net effect at the basin level, accounting for downstream effects, is difficult to track with current methods (Nelson et al., 2010; Jia, 2012; Perry and Hellegers, 2012; Simons et al., 2015).

These non-trivial dynamics currently revive an earlier debate on the water saving potential of irrigation improvements (Seckler, 1996; Cooley et al., 2008; Ward and Pulido-Velazquez, 2008; Perry et al., 2009; Pfeiffer and Lin, 2009; Christian-Smith et al., 2012; Brauman et al., 2013; Pfeiffer and Lin, 2014; Simons et al., 2015). Previous studies of water saving potentials may have been too pessimistic, as they implicitly assume that total irrigation water consumption is beneficial (Burt et al., 1997; Perry et al., 2009; Simons et al., 2015). Furthermore, estimates of irrigation efficiencies are mostly based on rough assumptions for regions or countries, without dynamic quantitative water accounting. Advanced estimates of global agricultural water consumption, of water saving and water productivity potentials at basin level require a dynamic simulation of irrigation systems, spatially explicit and in direct coupling with vegetation dynamics, climate and other biophysical dependencies.

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In global agro-hydrological models irrigation systems are insufficiently represented in this regard. For instance, many models only consider net irrigation requirements without accounting for water losses during conveyance or application (Haddeland et al., 2006; Siebert and Döll, 2010; Stacke and Hagemann, 2012; Elliott et al., 2015). Others employ globally constant indicative efficiency values from e.g. Brouwer et al. (1989), as a static input (e.g. Wriedt et al., 2009; Wada et al., 2013). These estimates were regionalized for the dominant irrigation system in each country by Rohwer et al. (2007) and since have been often referred to (e.g., Rost et al., 2009; Wriedt et al., 2009; Wada et al., 2011a; Schmitz et al., 2013; Chaturvedi et al., 2013; Elliott et al., 2014), but until today they remain rough indicative estimates. Assessments of future irrigation water requirements under climate change also have been carried out using static and country-based efficiencies, without accounting for local biophysical conditions (Fischer et al., 2007; Konzmann et al., 2013; Elliott et al., 2014). Sauer et al. (2010) endogenously determined the irrigation system based on biophysical and socioeconomic factors, but water fluxes are not simulated. To our knowledge, besides LPJmL (see below), PCR-GLOBWB is the only global model that calculates daily evapotranspiration and percolation losses per unit crop area based on surface and soil water balance, yet only for two crop classes without partitioning beneficial and non-beneficial water consumption (Wada et al., 2014).

With the aim of studying global irrigation systems based on an integrated, dynamic, and process-based approach, we implement a representation of the three major irrigation systems (surface, sprinkler, and drip) for various crop functional types (CFT) into the dynamic global bio-agrosphere model LPJmL. The new irrigation module goes beyond previous global modeling studies and replaces an existing scheme that is based on static efficiencies (Rost et al., 2008). It explicitly takes into account the daily surface and soil water balance (potentially limiting water withdrawal) and partitions irrigation water fluxes into transpiration (T), soil evaporation (E), interception loss (I), surface and subsurface runoff (R) and deep percolation (Dr), depending on daily weather conditions. Furthermore, we develop a new global dataset on the distribution

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of irrigation systems for each CFT at the 0.5° grid-level by combining AQUASTAT data on irrigation system distribution, cropland extent, and irrigation suitability.

Based on this data and modeling framework, we first present spatially explicit, dynamically retrieved global distribution of irrigation efficiency estimates based on a new, more precisely defined indicator: beneficial irrigation efficiency (E_b). Second, we provide new estimates for irrigation water components on the basis of significantly more spatial, temporal and process details compared to previous studies. Third, we investigate at basin level how much non-beneficially consumed water could be saved, and by how much crop water productivity could be increased, if irrigation system efficiencies were improved.

2 Methodology

2.1 Definition of irrigation efficiency

Irrigation efficiencies (E_i) are difficult to compare between studies, because there are various approaches to their definition and field measurements are difficult to assess (Burt et al., 1997; Perry et al., 2009). The generic definition is as follows (e.g. Bos and Nugteren, 1990; Seckler et al., 2003; Jensen, 2007):

$$E_\mathrm{i} = \frac{W_\mathrm{c}}{W_\mathrm{d}}, \tag{1}$$

where W_c is water consumption (evaporation from soil and water surfaces, transpiration, and interception) and W_d is water withdrawal, i.e. the amount of water diverted from rivers, reservoirs, lakes, or groundwater. The remainder, the non-consumed water, is the return flow (W_r), i.e. surface and lateral runoff and drainage or deep percolation. It thus equals the difference between diverted and depleted water (Lankford, 2006). Note that while in reality not all return flow is recoverable (due to degradation or inaccessibility; Fig. 1), LPJmL only considers the eventual outflow to oceans as non-recoverable.

Water consumption includes both beneficial and non-beneficial components. Plant transpiration belongs to the first category, as it occurs simultaneously with CO_2 uptake through the stomata and thus contributes to biomass build-up. The non-beneficial components, which are often of sizeable magnitude, include evaporation from soil and water surfaces, interception losses from vegetation canopies and puddles, and weed transpiration. Such non-beneficially consumed water is lost from the system and forms a real saving potential that is not reflected in E_i (Fig. 1). This has already been proposed by Burt et al. (1997), but due to technical challenges to its measurement, evaporation could not be separated from beneficial consumption and thus E_i was established as the common efficiency indicator. Here, we refine that definition and emphasize the use of a more precisely defined indicator, *beneficial irrigation efficiency* (E_b), given by the ratio of transpiration (T) and withdrawals:

$$E_\mathrm{b} = \frac{T}{W_\mathrm{d}} = E_\mathrm{c} \cdot E_\mathrm{f}. \tag{2}$$

E_b is further the product of conveyance efficiency (E_c) and field application efficiency (E_f). E_c relates to water transport losses from the source to the field:

$$E_\mathrm{c} = \frac{W_\mathrm{f}}{W_\mathrm{d}}, \tag{3}$$

where W_f is the amount of water that reaches the field. E_f relates to the water application on-field:

$$E_\mathrm{f} = \frac{T}{W_\mathrm{f}}. \tag{4}$$

Irrigation efficiency thus defined is scale-dependent, both in time and space. E_b is a valid indicator for assessing irrigation system performance at the field (and grid cell) scale, but it does not allow assessing water saving potentials at the basin level, since it does not take into account that return flows remain partly available for downstream reuse. In this respect, the term *effective efficiency* was introduced, defined as beneficial consumption (W_{bc}) per unit of water consumed (W_{c}), which includes that return flows are assumed accessible (e.g. Keller and Keller, 1995; Seckler et al., 2003; Jensen, 2007). For our analysis of water savings we focus on the reduction of non-beneficial consumption (W_{nbc}), and therefore we employ the inverse of effective efficiency, the *ratio of non-beneficial consumption* and total consumption:

$$\text{RNC} = \frac{W_{\text{nbc}}}{W_{\text{c}}}. \tag{5}$$

Throughout this study irrigation efficiencies are calculated from sums of daily water fluxes over the growing season on the irrigated fraction of each 0.5° × 0.5° grid cell in mm. As we use these annual values, water remaining in the soil storage is negligible for calculating irrigation efficiencies.

Moreover, we define crop water productivity as:

$$\text{CWP} = \frac{Y_{\text{irr}}}{W_{\text{tc}}}, \tag{6}$$

where Y_{irr} is yield production in kcal from irrigated crops and W_{tc} is total (blue and green) crop water consumption in liters. The model is able to trace the daily flows of both green water (directly originating from precipitation and infiltrating into the soil) and blue water (diverted from sources like rivers, lakes, reservoirs, and groundwater). Hereinafter, irrigation water fluxes always refer to the unfrozen blue water fraction unless specified otherwise (see Rost et al., 2008 for details).

2.2 Suitability of the dynamic process model to simulate irrigation systems

The model LPJmL globally represents biogeochemical land surface processes of vegetation and soils (Bondeau et al., 2007; Rost et al., 2008; Fader et al., 2010),

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simulating daily water and carbon fluxes in direct coupling with the establishment, growth, and productivity of major natural and agricultural plant types.

Spatio-temporal distribution of natural vegetation, represented through 9 plant functional types (PFTs), is dynamically simulated based on climatic and carbon dioxide forcing (Sitch et al., 2003). Agricultural land is represented by 12 specified CFTs, a class “others” including a suite of crops collectively parameterized as annual crops, and pastures (Bondeau et al., 2007), all either irrigated or rainfed. The spatial distribution of CFTs and their irrigated fraction is prescribed (see Sect. 2.5).

Photosynthesis modeling in LPJmL follows a modified Farquhar et al. (1980) approach and daily crop carbon assimilation is allocated to harvestable storage organs (e.g. cereal grain) and three other pools (roots, leafs, stems). Sowing dates are dynamically calculated based on climatic and crop conditions (Waha et al., 2012). Crops are harvested when they reach maturity, defined either through a CFT-specific maximum value of daily accumulated phenological heat units or expiration of the growing season. Storage organs are subsequently removed from the field. Root growth and distribution within soil layers is CFT-specific, while the soil profile is discretized into 5 hydrologically active layers and bedrock (Schaphoff et al., 2013).

Plant growth is currently not directly nutrient-limited in LPJmL, yet constrained by temperature, radiation, water and atmospheric CO_2 concentration. We calibrate crop yields with national FAO statistics based on three dynamic model parameters (as in Fader et al., 2010) to account for CFT-specific management intensities.

LPJmL partitions precipitation (prec) and applied irrigation water into interception, transpiration, soil evaporation, soil moisture, and runoff. Infiltration rate of the surface soil layer is a function of the saturation level (Eq. A1). Surplus water that cannot infiltrate (iteratively in 4 mm slugs) generates surface runoff. Subsurface soil water above saturation runs off in lateral direction, while remaining soil water above field capacity (W_{fc}) percolates to the layer beneath, depending on its soil water content and hydraulic conductivity. Globally, 13 soil types are differentiated, according to their water holding capacity (WHC), hydraulic conductivity and soil texture (Schaphoff et al., 2013).

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Surface and lateral runoff and seepage groundwater runoff, which is the percolation from the bottom soil layer, are added to cell runoff and are subsequently available for downstream reuse, routed along the river network.

Beneficial water consumption, i.e. transpiration, is calculated as the minimum of atmospheric demand (D), equal to potential evapotranspiration (PET) in the absence of water constraints, and actual root-available soil water constrained by plant hydraulic traits (supply S). PET is computed after Priestley–Taylor but modified by above-plant boundary layer dynamics (Gerten et al., 2007). If D exceeds S, crops begin to experience water stress (Eqs. A1 and A2). Evaporation is a function of PET, soil water content in the upper 30 cm, vegetated soil cover and radiation energy (Eq. A3). Interception loss (I) is a function of leaf area index (LAI), the daily fractional vegetation coverage, leaf wetness, and PET (see Eqs. 9 and 10 below).

Moreover, we account for household, industry and livestock water use (HIL, assumed to be consumed prior to any irrigation; see Sect. 2.5) and include a representation of dams and reservoirs to improve the simulation of available surface water (Biemans et al., 2011).

Thus, water fluxes are simulated in considerable detail, in direct dynamic coupling with vegetation dynamics, and responsive to climatic conditions. LPJmL is therefore well suited for studying water fluxes associated with differentiated irrigation systems in an internally consistent and process-based manner.

2.3 Implementation of the new irrigation scheme

We implement the three major irrigation systems – surface, sprinkler, and drip – according to their generic characteristics in direct coupling to the model's soil water balance, which overcomes the earlier scheme of nationally fixed efficiencies as in (Rost et al., 2008). Irrigation systems differ in the way they distribute water across the field. Surface systems (basin and furrow combined) flood the field, sprinkler uses pressurized sprinkler nozzles and micro/drip is the most cost-intensive system using localized water application directly to the plants' root zone. Indicative efficiency

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values (E_i) associated with the three system are roughly 30–60, 50–70 and 70–90 %, respectively (Brouwer et al., 1989; van Halsema and Vincent, 2012).

In our model, irrigation water is supplied based on daily soil water deficit. Daily net irrigation requirement (NIR, mm) is requested for withdrawal, if S falls below D. We define NIR as the amount of water required in the upper 50 cm soil to avoid crop water limitation. It is calculated to meet field capacity:

$$\mathrm{NIR} = \max(0, (W_{\mathrm{fc}} - w_{\mathrm{a}})), \tag{7}$$

where w_a is the actual available soil water in mm. Due to the above-described system inefficiencies, additional water needs to be requested to meet crop water demand. Therefore, we account for conveyance efficiency and calculate application requirements (AR) for each system, which add up to gross irrigation requirements (GIR, mm), the water amount requested for abstraction (Fig. 2):

$$\mathrm{GIR} = \frac{\mathrm{NIR} + \mathrm{AR} - \mathrm{Store}}{E_{\mathrm{c}}}, \tag{8}$$

where Store is a storage buffer (see below).

For pressurized water transportation (sprinkler and drip), E_c is set to 0.95, as we assume inevitable losses from leakage of 5 % (Brouwer et al., 1989). We associate surface irrigation with open canal transportation and we further link E_c to the hydraulic conductivity (K_s) of the soil type. E_c estimates from Brouwer et al. (1989) are adopted, see Table 1. We assume half of conveyance losses are due to evaporation from water surfaces and the remainder is drainage and added to return flow.

AR is the additional amount of water necessary to distribute irrigation uniformly across the field, indicative of the farmer's estimate of application losses (that are simulated by the model). We calculate AR as a system-specific scalar of the free water capacity:

$$\mathrm{AR} = \max(0, (W_{\mathrm{sat}} - W_{\mathrm{fc}} - W_{\mathrm{pwp}}) \times \mathrm{du} - w_{\mathrm{fw}}), \tag{9}$$

where W_{sat} and W_{pwp} are soil water content at saturation and wilting point, respectively, in mm; du is the water distribution uniformity scalar, depending on the irrigation system (Table 1) and w_{fw} is the available free water (actual soil water content between saturation and field capacity).

Surface irrigation systems use large amounts of water to flood the field in order to uniformly distribute water, which results in considerable surface runoff and seepage (see our analysis below, and Rogers et al., 1997). This is represented through du = 1.15, leading to temporary over-saturation of the field. For sprinkler systems, du must not be smaller than 0.55 to securely deliver NIR into the upper 50 cm of the soil (Fig. S1). Drip systems apply water localized to the plant and therefore distribution requirements are much lower, with du = 0.05 average yield levels are slightly below the potential (modest form of deficit irrigation), yet allocating salt leaching requirements (Fig. S1).

Daily GIR and HIL add up to the total withdrawal request in each cell. This demand is met from local surface water, including reservoir water and if not sufficient, requested from neighboring upstream cells (Fig. 2 and Biemans et al., 2011). Actually withdrawn irrigation water is always reduced by conveyance losses.

Irrigation scheduling is simulated to be controlled by prec and the irrigation threshold (it), which defines the allowed degree of soil water depletion prior to irrigation. In sensitivity analyses we found that it is dependent on the CFT. C4 crops (maize, tropical cereals, sugarcane) are less sensitive to drought stress, which can be explained with their particular treatment of the Calvin cycle and CO_2 assimilation. The maximum yield for C4 crops is at it = 0.7 (global median, Fig. S2). Values of it for C3 crops (0.8–0.9) are found to be affected by annual prec; paddy rice is always parameterized with it = 1 (Table 1). Available irrigation water is reduced by available precipitation and the amount that is not released (if $S >$ it, see Fig. 2) is added to Store (model-internal compensation for local water availability) and kept available until the next irrigation event.

Surface and drip systems are simulated to apply irrigation water below canopy, and sprinkler systems above-canopy with associated interception losses:

$$I = \mathrm{PET} \times \mathrm{pt} \cdot \min(1, \mathrm{wet}) \cdot f_{\mathrm{v}}, \tag{10}$$

where pt is the Priestley–Taylor coefficient (1.32), f_{v} is the fraction of vegetated soil cover, and wet is fraction of the day with wet leaf surface, calculated as:

$$\mathrm{wet} = \frac{\min(1, \mathrm{intc} \cdot \mathrm{LAI}) \cdot (W_{\mathrm{i}})}{\mathrm{PET} \cdot \mathrm{pt}}, \tag{11}$$

where intc is a CFT-specific interception storage parameter (Gerten et al., 2004).

Droplet evaporation with sprinkler systems, presumably $< 1.5\,\%$ of the applied water (Meyers et al., 1970; Rogers et al., 1997), is implicitly accounted for. Furthermore, we restrict surface runoff for sprinkler systems, such that irrigation water that reaches the soil surface infiltrates and can only run off laterally or percolate into deeper layers.

We design drip systems, in contrast, with a loss-free infiltration into the first two soil layers, i.e. no surface or lateral runoff are subtracted from W_{i}. Soil evaporation losses from drip systems (only blue water) are reduced by 60 %, to account for its localized subsurface application of water (Table 1).

2.4 Development of new input data set for grid-level irrigation system distribution

Currently, no sub-regional information on the global distribution of irrigation systems is available, which would provide the missing link to more accurate simulations of irrigation water requirements and performances. We therefore develop a new dataset of the global distribution of irrigation systems, for each grid cell and CFT (Fig. 3). Country-level shares of irrigation systems can be associated with a series of socio-economic and biophysical factors. A comprehensive explanation of these patterns is beyond the scope of this study, and here we simply adopt national statistics from AQUASTAT (FAO,

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2014). Each country is assigned the respective share of the three irrigation systems (Table S1 in the Supplement), which we further disaggregate to the grid cell and the CFTs through a decision tree approach, using the extent of irrigated areas by CFT (Porkka et al., 2015; Siebert et al., 2015) and an irrigation system suitability table. The CFT suitabilities for each irrigation system (Table 2) are determined based on restrictions due to soil type, the CFT-specific tolerance toward moisture depletion, the characteristic planting and harvesting techniques, the specific physical habit of the crop, and its economic market value (e.g. low market value crops are excluded from drip irrigation); based on Sauer et al. (2010) and Fischer et al. (2012) (see the Supplement for further details).

2.5 Simulation protocol

For this study, we ran LPJmL for the time period 1901–2009, forced with the Climate Research Unit's (CRU) TS 3.1 monthly climatology for temperature, cloudiness and wet days (Harris et al., 2014) and with the Global Precipitation Climatology Centre's (GPCC) precipitation data (Version 5) (Rudolf et al., 2010). Transient runs follow a 120 year spinup (recycling the first 30 years of input climatology) to bring sowing dates into equilibrium, which are fixed during the simulation period thereafter. Spatially explicit global information on cropland extent is obtained from the MIRCA2000 land use dataset (Portmann et al., 2010). The extent of areas equipped for irrigation from 1900 to 2005 is imported from Siebert et al. (2015), who provide an improved estimate of historic irrigation expansion with a total global extent of 306 Mha in 2005 (297 Mha in LPJmL, see Porkka et al., 2015).

Water use for non-agricultural sectors, HIL, account for 201 km^3 in the year 2000 based on recent estimates by Flörke et al. (2013). Our baseline simulation assumes that irrigation water withdrawal is constrained by local, renewable water storage, i.e. there is no implicit assumption about contributions from fossil groundwater or diverted rivers. If not indicated otherwise, results are presented as 1980–2009 averages.

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In addition to the current distribution of irrigation systems, we ran three synthetic scenarios to investigate the global performance of each system and to provide an estimate of the effect of irrigation system transitions. In these scenarios (hereinafter: All-Surface, All-Sprinkler, All-Drip) it is assumed that each system is respectively applied on the entire global irrigated area.

3 Results

3.1 Global patterns of irrigation efficiency

51 % of total global diverted irrigation water is simulated to be consumed (mean global area-weighted $E_\mathrm{i} = 56\,\%$) and 29 % are beneficially consumed, i.e. transpired (mean global area-weighted $E_\mathrm{b} = 34\,\%$), following our dynamic implementation. In Fig. 4 we show global spatial patterns of E_b, which are to a large extent determined by the irrigation system in use (Fig. 3), but as importantly, by its performance under local biophysical conditions and the present crop type. Extensive regions in Central, South, and South-East Asia with high shares of surface irrigation (widespread rice cultivation) show low efficiency values of $< 30\,\%$. North China plains with high irrigation intensity and mainly maize and wheat varieties exceed 50 %, but particularly Europe and North America stand out with values well above the global average due to relatively high shares of sprinkler and drip systems. The latter also applies to Brazil, South Africa and the Ivory Coast, where E_b exceeds 60 %. To illustrate system performances unaffected by their current geographical distributions, Fig. 5 displays E_b for the three irrigation systems separately, each assumed to be applied on all irrigated areas. Under this condition, global average values of E_b for surface, sprinkler and drip systems are 30, 52, and 73 %, respectively. Across all three scenarios, we find a remarkable low efficiency in Pakistan, North-East India and Bangladesh, opposed to above-average levels in the Mediterranean region, North China Plains and the US Great Plains. Moreover, E_b varies considerably between crop types due to different plant physiology

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and different cultivation regions/climate zones (Fig. 6; see next section). The values for maize, sugarcane and temperate roots are above the average across CFTs in our simulation, while rice, pulses, and rapeseed form the lower end. E_b is also sensitive to precipitation, soil properties and other biophysical factors, as characterized in Sect. 3.4.

3.2 Global irrigation water fluxes

Global irrigation water withdrawals simulated with the new irrigation scheme are 2396 km^3 per year, averaged for the time period 2004–2009. 1184 km^3 return to the river system, while 1212 km^3 are consumed (1413 km^3 including consumption from non-agricultural sectors HIL), of which 701 km^3 are beneficially consumed, i.e. transpired by crops (Table 3). The remainder, 511 km^3, is non-beneficially consumed and is indicative of the substantial water saving potentials associated with irrigation improvements (see Sect. 3.3 for details).

Figure 6 illustrates the decomposition of irrigation water fluxes for each CFT and all three irrigation systems. Transpiration is relatively constant across irrigation systems (irrigation target). However, on global average, drip systems achieve 7 % less transpiration (Table 3). This result reflects that drip irrigation systems generally do not aim to saturate the soil and thus conduct a modest form of deficit irrigation not designed to maximize yields but to save water.

Return flow with surface irrigation forms the major part of non-beneficial fluxes, exceeding by a factor of two the non-beneficial consumption (evaporation from soil and water surfaces). Sprinkler systems have a considerably lower return flow fraction (67 % difference between All-Surface to All-Sprinkler) and contribute only 13 % of withdrawals in the All-Drip scenario. Conveyance losses are significantly lower with sprinkler or drip systems due to pressurized conveyance. Evaporation losses are relatively similar between surface and sprinkler systems, while drip systems show lower losses due to their system design. Interception losses with sprinkler systems (surface and drip apply water below canopy) form only a minor contribution to non-beneficial fluxes (Fig. 6).

3.3 Potential of irrigation system transitions

We simulated three theoretical "all-one-type" scenarios to investigate the global potential of irrigation system transitions. Replacing a surface system by sprinkler or drip systems could, on average, reduce the target value – non-beneficial consumption – by 52 and 75 %, respectively, while maintaining yield production at the global level (indicated by W_{bc} in Table 3). Withdrawal amounts would decrease by 45 and 79 %, and return-flows by 63 and 91 %, respectively.

While upgrades of irrigation systems thus appear to be beneficial locally and mostly easing water diversion, major reductions of return flows can also have negative local impacts on downstream users. To evaluate the net effect along rivers and identify river basins that are most sensitive to irrigation improvements, we assessed water saving potentials and changes in water productivity at river basin level for each transition scenario.

Currently, the ratio of non-beneficial consumption to total consumption is particularly high in some South Asian basins (Indus, Ganges, Mahanadi), Korea, the Sahel, and Madagascar (Fig. 7a). A transition from surface to sprinkler or drip systems is simulated to cause a distinct reduction in non-beneficial consumption mainly in these very regions, but also in temperate regions in Europe, North America, the Yangtze basin, Brazil, Argentina and South Africa (Fig. 7c and e). Mean basin-level reductions in non-beneficial consumption would amount to 54 % when moving from surface to sprinkler systems and 76 % when moving to drip systems (Table 4).

Current global mean water productivity is simulated to be 2.83 $\mathrm{kcal\,L^{-1}}$, but with very distinct regional patterns (Fig. 7b) due to a combination of many factors, mainly heterogeneous crop management intensities and current distribution of irrigation systems. We find a strong gradient from very low values ($< 2\,\mathrm{kcal\,L^{-1}}$) in Central America, Sub-Saharan Africa and South Asia, to medium levels in East Asia and high values of 4–5 $\mathrm{kcal\,L^{-1}}$ across North America and Europe. Replacing a surface system by a sprinkler or drip system would increase crop water productivity by (globally

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averaged) 9 and 15 %, respectively (Table 4). In individual basins, e.g. in extensive regions in Central and South Asia, Mediterranean region and the Nile, in the Sahel, in South Africa and in the Colorado basin, effects would be even more pronounced: at basin level production increases of 20 % (sprinkler) and 30 % (drip) would be attained (Fig. 7d and f).

Moreover, we show explicitly that transpiration and total water consumption do not form a one-to-one relation, as is often argued when discussing the potential of irrigation transitions (e.g. Perry et al., 2009). Surface, sprinkler or drip systems follow individual slopes, disclosing saving potential (Fig. 8). Overall, this pilot analysis of irrigation system transitions shows that water saving potentials and water productivity improvements could be significant in many regions, on local farms and across basins.

3.4 Evaluation of simulation results

Our estimates of global irrigation water withdrawal and consumption (W_d: 2396 km^3, W_c: 1212 km^3) agree well with previously published, but not always state-of-the-art estimates. Country statistics for W_d reported for the period 1998–2012 are 2722 km^3 (FAO, 2014), while model estimates range between 2217 and 3185 km^3 (Wada and Bierkens, 2014; Döll et al., 2014, 2012; Siebert and Döll, 2010; Wada et al., 2011b; Alexandratos and Bruinsma, 2012). Estimates for W_c range from 927 to 1530 km^3 (Hoff et al., 2010; Chaturvedi et al., 2013; Döll et al., 2014). Döll et al. (2012) concludes that 1179 km^3 (Wada and Bierkens, 2014, 1098 km^3) stem from surface water and an additional 257 km^{3}yr from groundwater resources. This is supported by Wada et al. (2012), who also point out that non-renewable groundwater abstractions are expected to contribute 20 % to the global GIR. In this study we did not account for fossil groundwater and desalination. However, 80 % of groundwater abstractions are assumed to be recharged by return flows (Döll et al., 2012), thus it is plausible that W_d as simulated here is somewhat lower than in studies that simulate (fossil) groundwater

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contributions. It is also important to point out that irrigation water estimates are sensitive to the precipitation database employed (Wada et al., 2014).

Irrigation efficiencies are difficult to validate due to nonhomogeneous definitions and problems in its measurement in the field. Nevertheless, in Table 5 we put our results into the context of comparable literature results. At the global level, we meet established indicative estimates of field application efficiency by Brouwer et al. (1989). These have been downscaled to the country level by Rohwer et al. (2007) and the area-weighted global mean is 49, 69, and 90 % for the three systems, respectively. Another independent estimate of field efficiency at the sub-continent level is provided by Sauer et al. (2010) with global mean values of 42, 78, and 89 %. Our estimates are well in line with these numbers, although some regional patterns from Sauer et al. (2010) are not represented in our results (Table 5). They find very low surface irrigation efficiencies in MENA and SSA, while we arrive at slightly above-average values in MENA and particularly low values in South Asia, which is supported by Döll and Siebert (2002) and Rosegrant et al. (2002). For Malaysia, e.g. Ali et al. (2000) confirms below-average values. Furthermore, our estimates of global water productivity agree very well with previous estimates (e.g. Brauman et al., 2013; Zwart and Bastiaanssen, 2004; Rosegrant et al., 2002). Overall, the performance of our new irrigation model is well in line with the patterns reported in previous studies (while being much more detailed in terms of process representation, spatial and temporal patterns), rendering this implementation operational.

Simulated irrigation water fluxes (and thus efficiency patterns) depend on a multitude of factors: crop type, local climatic conditions (e.g. prec, PET), crop phenology, LAI, length of the growing season, and soil parameters. With correlation analyses (Fig. 9), we show that water fluxes from each simulated irrigation system follow reasonable biophysical dependencies, in spite of a multitude of confounding processes. For instance, return flow mainly depends on prec and WHC; WHC is more relevant for surface systems, while prec appears to be most decisive for drip systems. Aboveground biomass affects soil evaporation negatively and interception losses positively. Precipitation during the growing season can lead to leaching of soil water that originated from irrigation, which can oppress efficiency indicators. Geographical patterns in the ratio of non-beneficial consumption (Fig. 7a) and of return flow determine gradients in irrigation efficiency (Fig. 5), which are thus plausible from a biophysical perspective.

4 Discussion

4.1 Significance of results

This study presents for the first time spatially and temporally explicit estimates of irrigation system performances (separately for the world's major crop types) at the global level, based on dynamic simulation of underlying local biophysical conditions. Hence, this study advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems as likely required in view of projected increases in world food demand. Our global irrigation water estimates and regional efficiency values are well in line with existing literature, but we find distinct spatial patterns that were not available before with such level of spatial, temporal, and process detail. Generally, it has been assumed that economic and agronomic drivers control spatial patterns of irrigation efficiencies (e.g. Sauer et al., 2010; Schmitz et al., 2013). Here we show that biophysical factors additionally have non-trivial effects on spatial patterns of system efficiencies.

Moreover, we show that enhanced irrigation techniques offer substantial opportunities to reduce irrigation water consumption while maintaining beneficial transpiration rates and, thus, crop production levels at the river basin level. We also identify river basins in South Asia, in the Mediterranean region, and the Sahel to be most sensitive to irrigation improvements as resulting from the combination of local crop types, climate and soil conditions and the current irrigation system. These findings contribute to the current debate on global opportunities associated with irrigation

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systems and results suggest that irrigation improvements are an important contribution to sustainably increase food production (among various other means, e.g. Kummu et al., 2012; Jalava et al., 2014). The new implementation is a prerequisite for follow-up studies of global crop production and yields under changing climate, production potentials of irrigation system transitions and expansions, and climate change impacts on irrigation efficiencies and demands.

4.2 Modeling issues

Previous LPJmL estimates of W_d and W_c (Rost et al., 2008; Konzmann et al., 2013) are now improved with this study. Those earlier estimates tended to be lower than comparative studies, because first, the extent of irrigated land was scaled down for reasons of multi-cropping (see Fader et al., 2010, for details). Second, we believe that the new implementation accounts for a more realistic simulation of irrigation fluxes and the soil water balance, which on the one hand increases water demands, and on the other hand improves discharge dynamics, in that applied irrigation water percolates through soil layers and runoff rates are more realistically delayed.

Generally, not all of the area equipped for irrigation is being irrigated every year, especially where supplementary irrigation is practiced. Such deficits can be considerable, mostly in temperate and humid regions (Siebert et al., 2010, 2015). We claim that they are mostly considered in our simulations as it is a key component of our irrigation module to dynamically trigger or pause the application of irrigation water based on soil water deficit and blue water availability. However, variations in irrigated area due to other reasons (not reflected in the land use input dataset) cannot be accounted for.

The CFT group “others” pools a variety of crops including perennial and annual types (e.g. cotton, citrus, coffee) but is generically parameterized as perennial grassland. Therefore, the growing season length for these crops is systematically overestimated, which may lead to somewhat too high estimates of total water use and demand. This potential overestimation might be counterbalanced by an overestimation of accessible return flow, as LPJmL cannot account for the fact that return flows are only partly recoverable (physically or economically), and that they are often degraded through nutrient leaching and salinity.

Irrigation can have other purposes than satisfying crop water requirements, like salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. These irrigation applications are however beyond the scope of this study and are not explicitly considered in the withdrawal demand. Salt leaching below the root zone, as for the most significant of those, is critical in regions with marginal precipitation and can be controlled through applying an additional 5–10 % irrigation water (Jensen, 2007). Figure 6 shows that in our implementation the runoff share with drip irrigation is, on average, large enough to meet this requirement.

Irrigation improvements can also be achieved by means other than completely replacing the system, e.g. through better scheduling (incorporating climate and soil data to precisely meet crop water demand), advanced management (deficit irrigation) and technical improvements. For instance, much water might be saved from evaporation and seepage if open canal conveyance systems were replaced by lined or pressurized installations. For the purpose of simplicity, in this study we bundle these various opportunities into the three different simulated generic systems and represent improvements through system transitions.

4.3 On irrigation system transitions

From a sustainability perspective, the primary objective in regions with irrigation overdraft is the reduction of irrigation water consumption. In face of a growing human population and various rapidly approaching planetary boundaries (Steffen et al., 2015), an immediate question thus is, by how much global crop water productivity and crop production can be improved with sustainably available water resources. Water saved through improved irrigation systems could allow either for an expansion of irrigated areas or for a production increase on irrigated yet water-limited farms. Throughout this paper we argue that the water saving potential is mostly constrained to the non-beneficially consumed fraction, as return flows are often accessible downstream. Egypt's Nile valley is an example of a multiple use-cycle system with a high basin-level efficiency but low local efficiencies (Keller and Keller, 1995).

Many authors thus argue that irrigation efficiencies add up close to 100 % at the basin level and therefore assume that water saving potentials through efficiency improvements are very limited (Seckler, 1996; Perry et al., 2009; Frederiksen and Allen, 2011). These findings are based on an assumption that crop transpiration follows a one-to-one relation with water consumption (Perry et al., 2009); saving potentials within the consumed fraction are largely neglected. Herein, we show that transpiration and consumption are not as closely linked as previously assumed, and that adapting modern irrigation techniques can indeed bring this dependency closer to the one-to-one line (Fig. 8). Accordingly, we show that transpiration rates (hence crop production) can be maintained while cutting the consumed volume in many regions at the basin level.

However, the implementation of such technical water saving potential does not imply that necessarily less water would be diverted. Farmers' decisions are often driven by maximizing their return and rarely by environmental concerns; if they pursue efforts to save water, they often use it to expand their irrigated areas or shift to higher value crops, rather than loosing water allocations (Ward and Pulido-Velazquez, 2008; Perry and Hellegers, 2012; Pfeiffer and Lin, 2014; Shah, 2014). From a food security perspective, however, irrigation improvements drive water productivity and thus increase gross crop yield, consuming the same amount of water.

Nevertheless, increasing irrigation systems at the global scale while respecting sustainability boundaries, requires a complex combination of substantial investments, institutional water policy regulations, and cultural changes. Intelligent water pricing (currently rarely reasonable) is for instance a measure to achieve trade-offs at basin level through economic incentives (e.g. Molden, 2007; Molle and Berkoff, 2007; Ward and Pulido-Velazquez, 2008).

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Higher technology irrigation systems can have manifold co-benefits, e.g. improved crop quality, conserving nitrate groundwater concentration, reducing water logging, saving energy, and reducing greenhouse gas emissions (e.g. Gleick et al., 2011; Christian-Smith et al., 2012; Calderón et al., 2014). Low-cost drip systems for smallholder farmers can help alleviate poverty in poor regions (e.g. Postel et al., 2001; Kijne et al., 2009; World Bank, 2010; Dillon, 2011; Burney and Naylor, 2012). They can boost water productivity, but are likewise prone to misuse and salinization (Belder et al., 2007; Hillel, 2008; Comas et al., 2012).

Overall, this study suggests that the potential of irrigation improvements might be more substantial than often anticipated in recent discussions. Nonetheless, such investments should be combined with other measures available to sustainable intensification (e.g. mulching, reduced tillage, and rain-water harvesting).

5 Conclusions

This study presents for the first time spatially and temporally explicit estimates of global irrigation system performances for the world's major crop types, based on dynamic simulation of underlying local biophysical conditions. Hence, this study significantly advances the global quantification of irrigation systems while providing a framework for assessing potential future transitions in these systems. We arrive at an estimate of global annual irrigation water withdrawal of 2396 km^3 (2004–2009); irrigation water consumption is calculated to be 1212 km^3, of which 511 km^3 are non-beneficially consumed. We find distinct spatial patterns in irrigation efficiency governed by biophysical conditions, which have been largely neglected in most previous studies. This new map of dynamically retrieved irrigation efficiencies is provided for incorporation into other global hydrological and agricultural studies, serving as a prerequisite e.g. for refined simulation of crop yields under conditions of future climate change and growing food demand. At the river basin level, i.e. accounting for downstream effects, we reveal, for many basins, the potential for sizeable reductions in non-beneficially consumed water (54–76 %) and related significant increases in crop water productivity (9–15 %) through transitions from surface to sprinkler or drip systems. These findings clearly suggest that irrigation system improvements should be considered an important means on the way to sustainable food security.

Appendix: Water balance equations

Infiltration rates In for soil layer l:

$$\mathrm{In}[l] = \mathrm{prec} \cdot \sqrt{1 - \frac{w_\mathrm{a}[l]}{W_\mathrm{sat}[l] - W_\mathrm{pwp}[l]}}, \tag{A1}$$

where w_a is the actual available soil water content, W_sat and W_pwp are soil water content at saturation and wilting point, respectively, in mm. Soil water supply S is calculated as:

$$S = E_\mathrm{max} \cdot w_\mathrm{r}, \tag{A2}$$

where E_max is the maximum transpiration rate in mm d^{-1} (Gerten et al., 2004) and w_r is relative soil moisture available to roots. Atmospheric demand D is calculated as:

$$D = \frac{f \cdot \mathrm{PET} \cdot \mathrm{pt}}{1 + \frac{g_m}{g_\mathrm{pot}}}, \tag{A3}$$

where f is the fraction of the day with dry canopy (condition to transpire), PET is retrieved according to the Priestley–Taylor method and pt is the maximum Priestley–Taylor coefficient (1.391), g_m is a scaling coefficient (3.26 mm s^{-1}), and g_pot is the potential canopy conductance (Gerten et al., 2007).

The Supplement related to this article is available online at doi:10.5194/hessd-12-3593-2015-supplement.

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Author contributions. J. Jägermeyr developed the model code and performed the simulations. J. Heinke and S. Schaphoff contributed to code development. M. Kummu prepared landuse input data. J. Jägermeyr prepared the manuscript. D. Gerten, W. Lucht, and M. Kummu contributed to manuscript preparation.

Acknowledgements. This study received funding from the BMBF-funded GLUES project of the "Sustainable Land Management" programme (Code 01LL0901A), and the FACCE MACSUR project (031A103B), and by the EU FP7 project CLIMAFRICA (grant no. 244240). The work was also supported by ILRI, the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS), and the Academy of Finland funded project SCART (grant no. 267463). We will provide an online version of Fig. 4 (global distribution of irrigation efficiency estimates) as gridded input for other studies upon paper acceptance.

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Table 1. Parameterization of irrigation systems in LPJmL. Sensitivity analyses for parameter estimates are available in the Supplement (Figs. S1 and S2).

Irrigation system	Distribution uniformity scalar	Conveyance efficiency[1]	Soil evaporation	Interception	Runoff	Irrigation threshold[2]	Minimal irrig. amount
Surface	1.15	open canal: sand 0.7, loam 0.75, clay 0.8	unrestricted	no	surface, lateral, percolation	C4: 0.7 C3 (prec $<$ 900): 0.8 C3 (prec $\geq$ 900): 0.9 Rice: 1.0	1 mm
Sprinkler	0.55	pipe: 0.95		yes	lateral, percolation		
Drip	0.05		soil evap. of irr. water reduced by 60 %	no	none, only indirect precip. leaching		none

[1] Open canal conveyance efficiency depends on soil hydraulic conductivity (K_s): $K_s > 20$: sand, $10 \leq K_s \leq 20$: loam, $K_s < 10$: clay; 50 % of conveyance losses are assumed to evaporate, for loam and clay (higher K_s) and open canal conveyance the fraction is 60 and 75 %, resp. [2] Depending on crop type.

Table 2. Biophysical and technical irrigation system suitability by crop type (CFT), based on Sauer et al. (2010) and Fischer et al. (2012).

Crop type (CFT)	Surface	Sprinkler	Drip
Temperate cereals (wheat, rye, barley)	x	x	–
Rice	x	–	–
Maize	x	x	–
Tropical cereals (millet, sorghum)	x	x	–
Pulses (field peas)	x	x	x
Temperate roots (sugar beet)	x	x	–
Tropical roots (cassava)	–	–	–
Sunflower	x	x	x
Soybean	x	x	x
Groundnut	x	x	–
Rapeseed	x	x	–
Sugarcane	x	x	–
Others (e.g. cotton, vine, coffee, citrus)	x	x	x
Pastures	x	x	–

Table 3. Global annual sums (km^3) of irrigation water withdrawal (W_d), return flow (W_r), irrigation water consumption (W_c) further split into beneficial (W_{bc}) and non-beneficial consumption (W_{nbc}), and E_b (in %), given as 2004–2009 averages. Values are for actual conditions and the All-Surface, All-Sprinkler and All-Drip scenarios.

	Actual	All-Surface	All-Sprinkler	All-Drip
Withdrawal, W_d	2396	2701	1502	907
Return flow, W_r	1184	1409	517	128
Consumption, W_c	1212	1292	985	779
Beneficial consumption, W_{bc}	701	707	702	653
Non-beneficial consumption, W_{nbc}	511	585	283	126
Beneficial efficiency, E_b	34	30	52	73

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Table 4. Mean basin-level changes in non-beneficial consumption (W_{nbc}) and crop water productivity (CWP) through system transitions from surface to sprinkler and drip, respectively; area-weighted means over all simulated basins in %.

	Surface to Sprinkler	Surface to Drip
Change in W_{nbc}	−54 (±8)	−76 (±7)
Change in CWP	9 (±6)	15 (±9)

Table 5. Comparison of field application efficiencies (for reasons of comparison, we employ here the traditional definition: consumed per applied irrigation water) for major world regions compared with literature values in %. This study's results are area-weighted averages, based on current distribution of irrigation systems (Fig. 3).

World region	Surf	Sprink (this study)	Drip	Surf	Sprink (Rohwer et al., 2007)	Drip	Surf	Sprink (Sauer et al., 2010)	Drip
North America	52	76	87	49	68	90	50	85	93
South America	55	79	87	51	68	90	38	75	88
Europe and Russia	50	80	90	52	72	90	52	86	93
Mena	61	85	94	49	69	90	22	60	80
SSA	54	73	87	54	75	90	28	64	82
Central and East Asia	55	78	83	48	68	90	42	79	89
South Asia	47	80	91	48	68	90	32	68	84
SE Asia and Oceania	52	66	86	48	70	90	38	75	88
World	52	78	88	49	69	90	42	78	89

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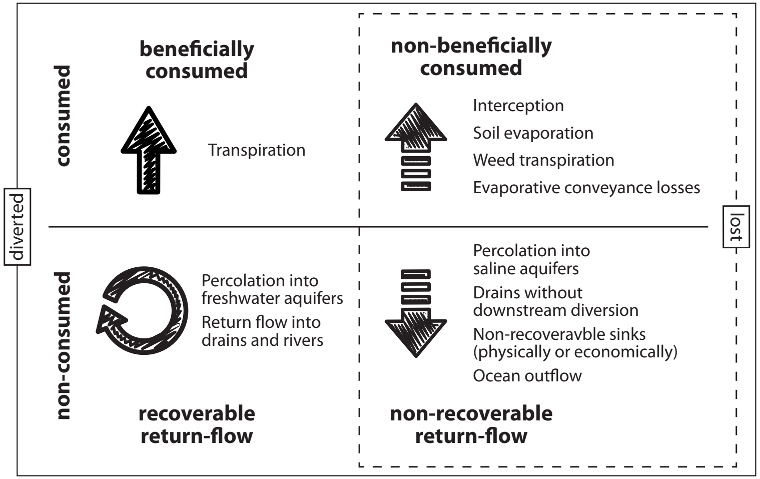
beneficially consumed
non-beneficially consumed
consumed
Transpiration
Interception
Soil evaporation
Weed transpiration
Evaporative conveyance losses
diverted
lost
non-consumed
Percolation into freshwater aquifers
Return flow into drains and rivers
Percolation into saline aquifers
Drains without downstream diversion
Non-recoveravble sinks (physically or economically)
Ocean outflow
recoverable return-flow
non-recoverable return-flow

Figure 1. Pathways of irrigation water fluxes. All diverted water is either consumed (non-)beneficially, or re-enters rivers, reservoirs and aquifers, which makes it recoverable through return flow. Non-beneficial consumption and non-recoverable return flow can be considered losses (at the basin scale).

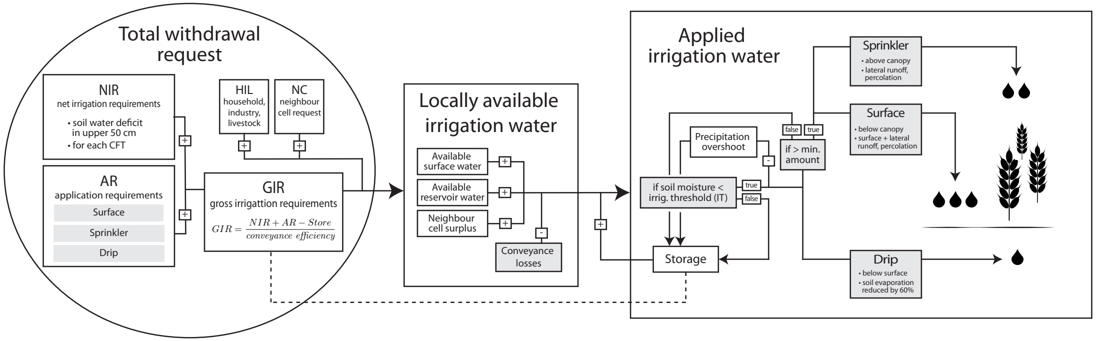
Total withdrawal request
NIR
net irrigation requirements
• soil water deficit in upper 50 cm
• for each CFT
HIL
household, industry, livestock
NC
neighbour cell request
AR
application requirements
Surface
Sprinkler
Drip
GIR
gross irrigattion requirements
GIR = NIR + AR − Store / conveyance efficiency
+
-
Locally available irrigation water
Available surface water
Available reservoir water
Neighbour cell surplus
Conveyance losses
Applied irrigation water
Sprinkler
• above canopy
• lateral runoff, percolation
Surface
• below canopy
• surface + lateral runoff, percolation
Drip
• below surface
• soil evaporation reduced by 60%
Precipitation overshoot
if > min. amount
if soil moisture < irrig. threshold (IT)
true
false
Storage

Figure 2. Irrigation water flows in LPJmL from plant-specific net irrigation requirement to actual field application. Variables represented in grey-shaded boxes depend on system-specific parameters that are presented in Table 1.

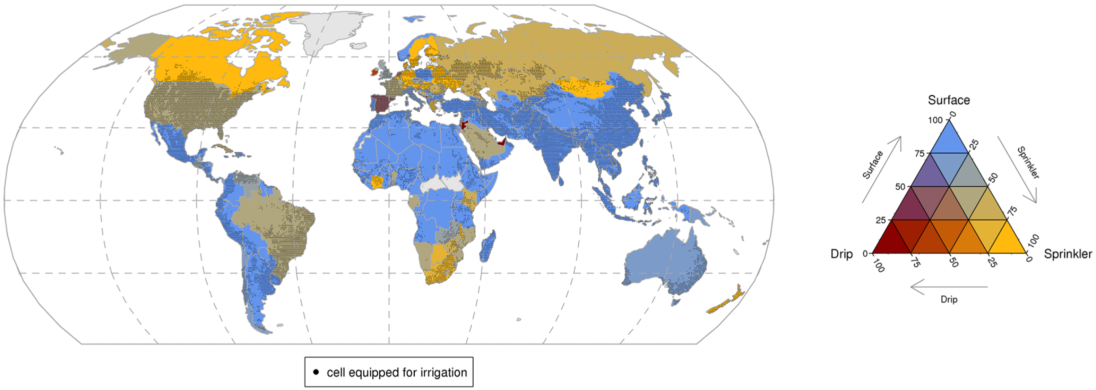
Surface
Drip
Sprinkler
100
75
50
25
0
Surface
Sprinkler
Drip
cell equipped for irrigation

Figure 3. Global distribution of irrigation systems at country level, based on AQUASTAT statistics. Cells that include irrigated areas are hatched, based on Siebert et al. (2015).

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12, 3593–3644, 2015

Dynamic global simulation of irrigation systems

J. Jägermeyr et al.

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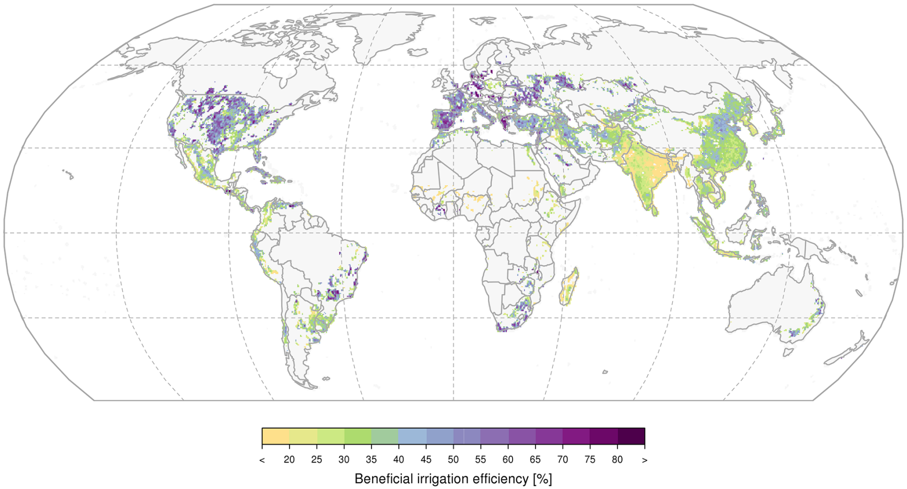

<
20
25
30
35
40
45
50
55
60
65
70
75
80
>
Beneficial irrigation efficiency [%]

Figure 4. Global patterns of beneficial irrigation efficiency (E_b, ratio of transpired and diverted water) as area-weighted mean over CFTs (exclusive "others" and pastures) and based on the system distribution in Fig. 3.

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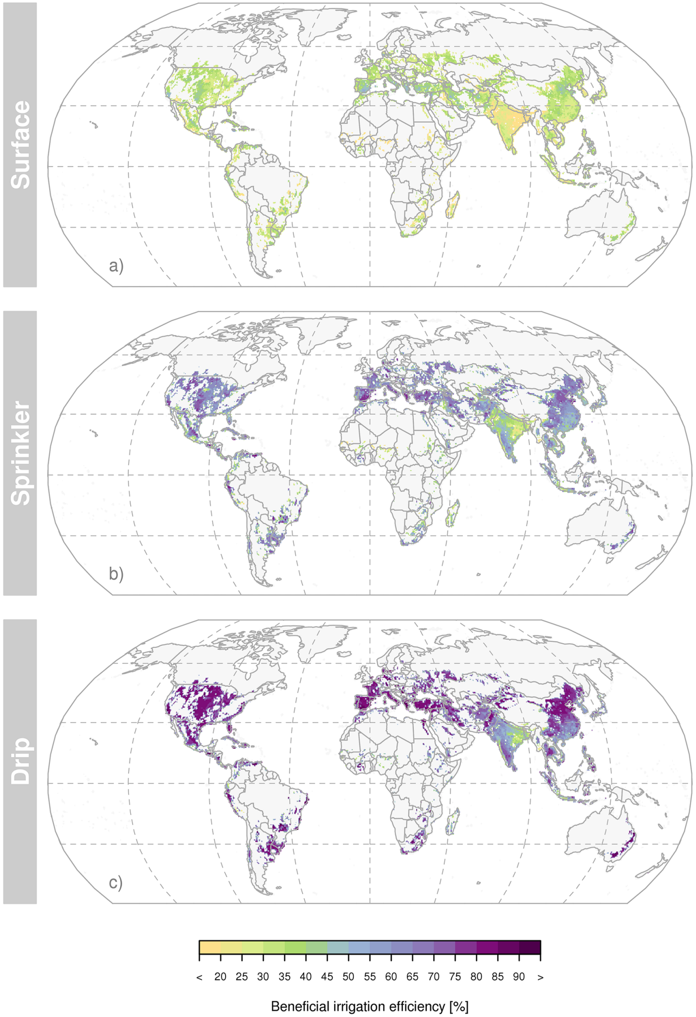
Surface
a)
Sprinkler
b)
Drip
c)
< 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 >
Beneficial irrigation efficiency [%]

Figure 5. Global patterns of beneficial irrigation efficiency (E_b, ratio of transpired and diverted water) for each irrigation system **(a)** surface, **(b)** sprinkler, **(c)** drip, calculated as area-weighted mean over CFTs (excl. "others" and pastures). This figure is based on theoretical scenarios, in which each system is respectively assumed to be applied on the entire irrigated area.

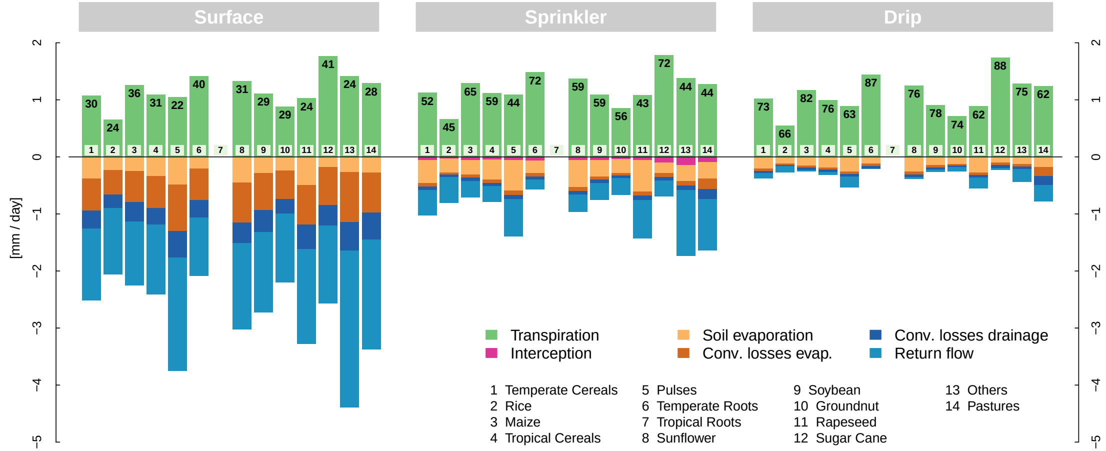

Figure 6. Decomposition of beneficial and non-beneficial irrigation water fluxes for each simulated CFT and irrigation system, in $\mathrm{mm\,d^{-1}}$ averaged over the respective growing seasons and cultivated areas. For better comparability, each system is individually applied on all irrigated areas assuming the same, optimal management. The number at the top of each stack represent the CFT-specific beneficial irrigation efficiency (E_b, in %). Tropical roots are not irrigated.

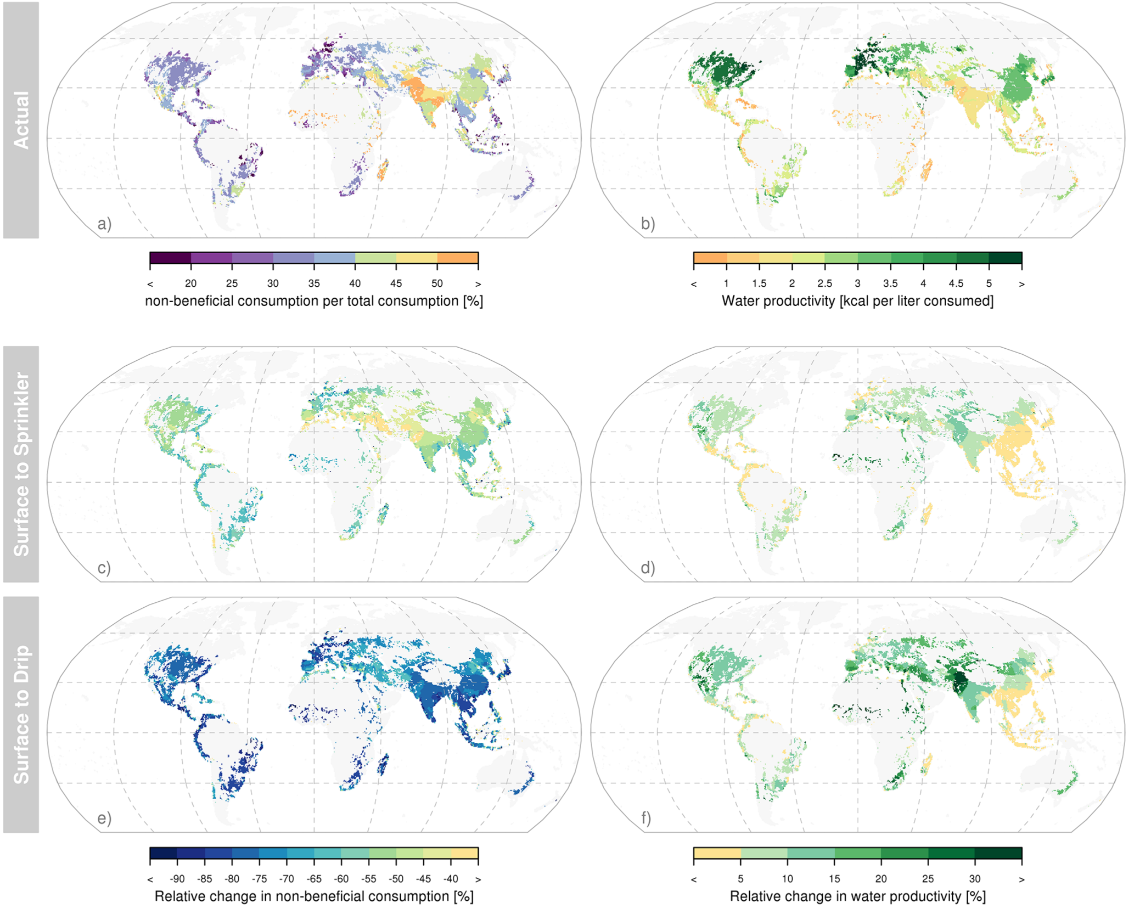
Actual
Surface to Sprinkler
Surface to Drip
a)
b)
c)
d)
e)
f)
< 20 25 30 35 40 45 50 >
non-beneficial consumption per total consumption [%]
< 1 1.5 2 2.5 3 3.5 4 4.5 5 >
Water productivity [kcal per liter consumed]
< -90 -85 -80 -75 -70 -65 -60 -55 -50 -45 -40 >
Relative change in non-beneficial consumption [%]
< 5 10 15 20 25 30 >
Relative change in water productivity [%]

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Figure 7. Basin-level aggregation of ratio of non-beneficial consumption and total consumption (RNC, **a**), and water productivity (kcal from irrigated crops per consumed liter of blue and green water, **(b)** given the current distribution of irrigation systems. Panels **(c–f)** show the relative change in E_b and water productivity given a transition from surface to sprinkler **(c, d)** and surface to drip systems **(e, f)**, respectively (All-surface, All-sprinkler, and All-drip scenarios). Pastures and “others” are excluded.

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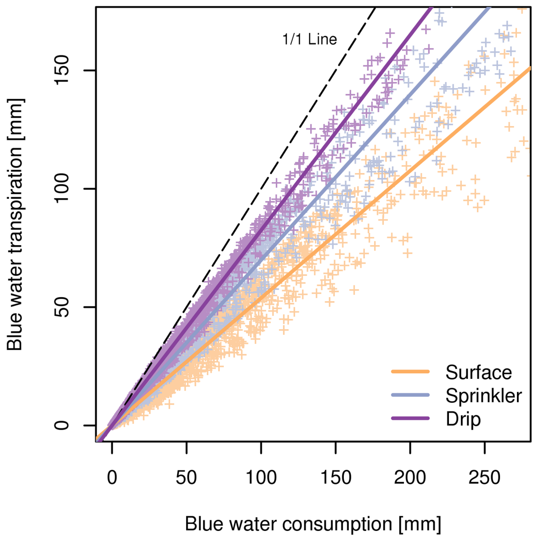

Figure 8. Relation of blue water consumption and blue water transpiration for the three scenarios All-Surface, All-Sprinkler, All-Drip and each grid cell, compared to the 1/1-Line.

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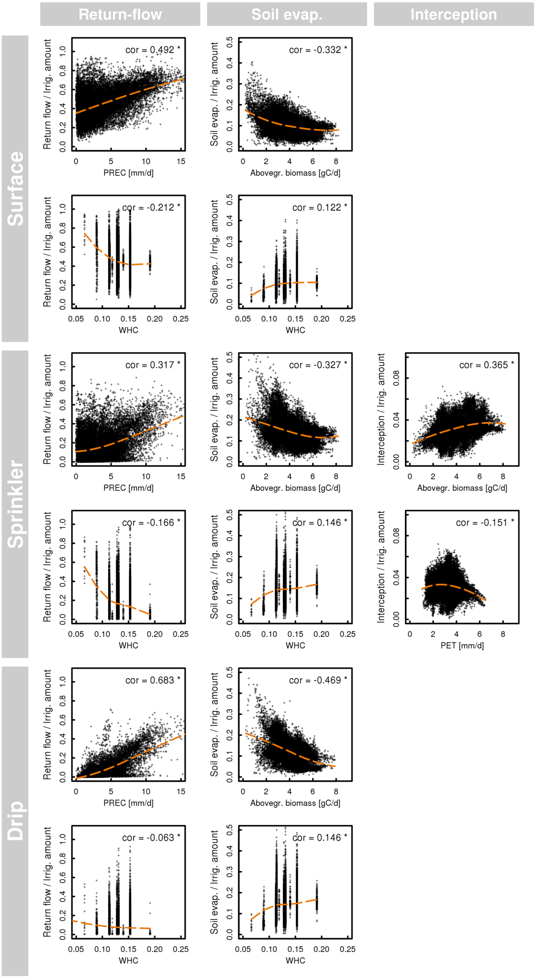

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Figure 9. Dependencies of non-beneficial irrigation water fluxes on its main biophysical driving factors (3 columns: return flow, soil evaporation, interception). Double rows represent the irrigation system: surface, sprinkler, and drip. Data is based on 12 crop CFTs from the All-Surface, All-Sprinkler and All-Drip scenario, respectively and country-scale management intensities are harmonized (calibration factors are set so as to represent systems with optimal management). Dashed lines indicate polynomial bias curve, "cor" refers to Spearman's correlation coefficient (*, if p value $< 10^{-9}$). PREC: precipitation, WHC: water holding capacity, PET: potential evapotranspiration.