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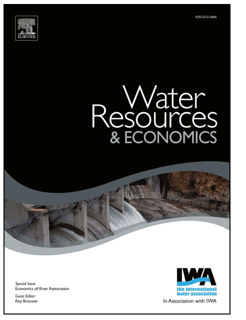

Projecting irrigation water requirements across multiple socio-economic development futures – A global CGE assessment

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Projecting irrigation water requirements across multiple socio-economic development futures – a global CGE assessment

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Key Points:

- Irrigation is included as a factor of production in a global CGE model which distinguishes between rainfed and irrigated crop production
- Global irrigation requirements in 2050 are projected to be 8.5-11% higher than in 2004
- All currently water-challenged regions maintain or even further expand the pressure over renewable freshwater resources
- Production of vegetables, fruits and wheat induces the largest increase in irrigation water requirements

Acknowledgments

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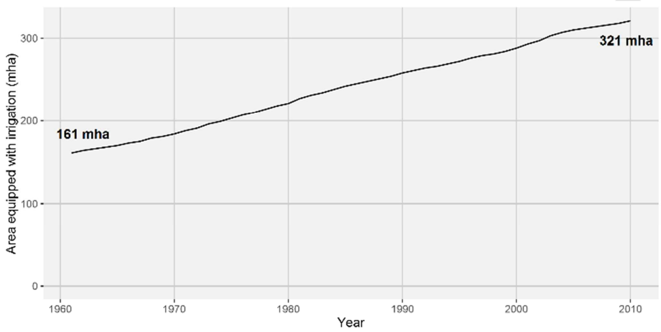
1. Introduction

1.1. Scope

Irrigated crop production is the single-most important blue water user representing 70% of total worldwide withdrawals [1]. Developing regions have an even higher share of withdrawals dedicated to irrigation due to the importance of agriculture in their economies. At the same time, meeting global crop demand relies to a large extent on enhancing moisture of water-deficient soils, with 40% of world crop output currently being obtained on irrigated land [1]. As a consequence, the use of irrigation has continuously grown in the past decades leading to a doubling of the global area equipped for irrigation in the 1961-2010 timeframe (Figure 1).

Figure 1 - Global area equipped for irrigation 1961-2010



Data source: FAOSTAT

Demand for agricultural goods is expected to further expand in the next half of century due to continued demographic and economic growth [1]. Therefore it is important to understand the role that irrigated production together with yield improvements and land-use changes will play in meeting this increased demand. Increases in water withdrawals for irrigation are thus anticipated especially in high-growth developing regions that are quickly running out of suitable cropland and in which equipping arable land with irrigation leads to a boost in yields.

Therefore, in this research, we seek to assess the future irrigation pressure over freshwater resources by taking into account alternative socioeconomic development storylines in the 2004-2050 timeframe. These storylines are derived from downscaled data of three Shared Socioeconomic Pathways (SSPs) [2]. Withdrawal pressure is expressed using the Irrigation Withdrawal to Availability (IWA) indicator i.e. irrigation water requirements relative to total renewable water resources. Irrigation water demand is derived using the RESCU-Water model (Resources CGE UCL Water) - a global dynamic recursive CGE model which uses irrigation freshwater as an explicit factor of production. The model distinguishes between irrigated and rainfed crop production thus allowing for a differentiated specification of yield improvements of the two land types involved. Water requirements in irrigation are therefore determined "bottom-up" by accounting for input substitution possibilities and technological advancements detailed for every region, crop class and growing method.

The paper is structured as follows. The remainder of this introduction section provides a critical view on past efforts in projecting freshwater uses at a global level. The RESCU model structure and scenario implementation are presented in Section 2. Section 3 presents the relevant model results – changes in crop output and irrigation requirements, irrigation pressure evolution using the IWA indicator, and changes in virtual water flows associated with international trade. The discussion of results and the consideration of limitations of this study are presented in Section 4. Section 5 then draws the conclusions.

1.2. Projections and modelling of freshwater uses

Over the past two decades, attention has been given to assessing whether freshwater availability will suffice to cover future demand. In this respect, various approaches have been used with each bringing new light into the present and future state of freshwater resources, but also facing methodological limitations. The first large-scale assessment was undertaken in Shiklomanov [3] where the specifics of individual uses are considered and past growth patterns of the relevant drivers (population, GDP, irrigated land, power production) are extrapolated to determine future freshwater demand. This high-level assessment method has been employed further in combination with hydrological models in the interest of representing water stress evolution at an increasingly fine geographical resolution [4]–[9]. The models used in these studies excel at having a spatially-detailed representation of freshwater resource distribution, however, they do not embed any underlying microeconomic behaviour driving freshwater demand in irrigation e.g. price signals impacts over crop demand, land conversion, crop substitution etc.

Partial-equilibrium economic modelling has aimed at offering a more detailed representation of freshwater demand given future patterns of crop output expansion. In the IMPACT model [10], water resources are divided into 320 Food Producing Units (FPU), structured along with country borders and major river basins. The model is used to assess future food security under income and population growth. Within each FPU freshwater is being allocated to 44 crop classes based on crop prices and on crop water requirements along the different crop growth stages. Limits on irrigation withdrawals are imposed when total demand exceeds available renewable resources. In IMPACT, the crop sector is considered the lowest priority freshwater user i.e. total available resources are determined by deducting non-crop water uses first. The model implements income effects through demand income elasticities and profit maximisation through an allocation of freshwater resources according to crop profitability. However, as partial-equilibrium, the model lacks an economy-wide view in the supply and allocation of factors of production across sectors given changes in relative prices. For instance, crowding-out effects of labour demand outside agriculture with subsequent impacts on crop production costs cannot be taken into account. To address some of these limitations, IMPACT is linked in [11] to a global CGE model [12] to incorporate cost effects over crop production coming from energy- and subsequently fertiliser price changes under different climate change mitigation scenarios.

The modelling of freshwater uses in crop production through a Computable General Equilibrium (CGE) framework has been undertaken extensively at a country-level [13]–[18], and is increasingly gaining attention in global modelling [19]–[25]. There are now different methods to represent water as an input to crop production using a global economic database as a starting point (see [26] for an overview). Most applications of global-level water modelling have focused on the relationship between the supply-side of water scarcity and the themes of international trade [27]–[29], food security [19], [30] and climate change [22], [25], [31]. However, less focus has been placed on the evolution of water demand coming socioeconomic development and its importance for the future state of water stress.

Except for the GTAP-based model used in [22], [24] and [30], in all these research efforts, total irrigation withdrawals are treated exogenously and therefore do not expand or contract as a function of market forces. For instance, in GTAP-W2 [31], because of the factor market clearing condition inherent to CGE models, it is implicit that any change in run-off induced by climate-change incurs a change in withdrawals in the same direction. In GTAP-BIO-W [33], water withdrawals are decided outside the model through changes in an irrigation water supply reliability (IWSR) index derived from the IMPACT model. Hence, in all regions for which the index remains unchanged, withdrawal changes do not occur regardless of the price pressures coming from an expansion of crop demand. In contrast, in [24], the water demand of different sectors is explained as a function of sectoral economic output and a sector-specific water intensity coefficient. Thus, demand expansion of irrigation water is explored in relation to different socioeconomic development pathways by using “top-down” calculations starting from an overall change in crop production. While this approach can be suitable for industrial and household water demand where water uses are heterogeneous, water inputs in irrigation are homogenous across crop types being determined by evapotranspiration. Therefore a “bottom-up” approach is more suitable in understanding the interactions between irrigation water requirements and crop demand changes. This is possible through a disaggregated representation of crop production across crop classes and growing methods (irrigated and rainfed) which allows for a differentiated representation of technological improvements and input substitution, and their impact on crop water productivities and implicitly water requirements.

Concerning the physical freshwater supply constraints, it is difficult to assess how much freshwater can be abstracted from the environment at a global scale and even more so to determine how much can be employed for irrigation. On the one hand, there is vast evidence that some river basins are currently being overexploited with a considerable reliance on groundwater pumping [34]–[37] thus no upper withdrawal limit can be considered unless exploring a sustainability scenario. On the other hand, without considering the evolution of other freshwater demand drivers (industry, services and households) by systematically using the same assumptions with regard to socio-economic development, it is not possible to ascertain the amount that is available to crop production even when a total withdrawal limit can be considered. Hence the present assessment of future freshwater requirements does not take into account physical limitations in irrigation freshwater supply associated with decreases in water tables or to the depletion of river flows. Nevertheless, it is important to acknowledge that it will become increasingly challenging to source the required volumes as withdrawals near or even exceed river basin recharge rates. Therefore the IWA indicator used in this paper should be regarded as an indicator of pressure and not as a reflection of actual future withdrawals.

2. Materials and methods

2.1. CGE modelling

The advantage of utilising a CGE framework to determine changes in freshwater withdrawals comes from the framework’s capability to capture factor allocation across sectors. CGE models typically consist of a multi-sectoral and multi-factor view of an economy in which all markets are cleared at the end of a simulation period. The effects of economic growth and those of changes in population can thus be captured on the supply side by tracking the accumulation of capital stock and the evolution of labour supply and labour productivity. On the demand side, as described in sections 2.2.4 and 2.2.6, socioeconomic development translates into changes in final demand given the spending behaviour of the different agents (households, government and investment).

Furthermore, as an input to production, irrigation needs to be represented in relation to the other factors in terms of substitution possibilities and feedback effects as a consequence of technological change. In this research, we capture the relationship between cropland productivity gains through yield changes and the demand for irrigation. Yield growths lead to a reduction in land requirements per unit of output and implicitly reduce the land market prices. These exogenous yield improvements then lower the total cost of production resulting in a rebound growth of demand for crops and subsequently of irrigation.

The use of a global CGE framework is also relevant for tracing the impact of international trade over freshwater withdrawals. With crops being some of the most intensely traded commodities, the extension of the analysis at a global level enables us to include the effects crop trade over irrigation withdrawal pressure. This allows us to analyse whether regions that are land or water constrained are likely to replace some of the domestic production of irrigation-intensive goods with imports and thus avoid further increases in pressure over its endowments.

CGE models can, therefore, be used to map the flows of 'virtual water' embedded in international trade. The virtual water concept was established in Allan [38] and is now used to determine the water footprint of world regions [39] and that of international trade [40], [41], [27], [42]. As our research focuses on irrigation, the virtual water results refer to the embodied blue water content associated to crop trade.

2.2. RESCU model overview

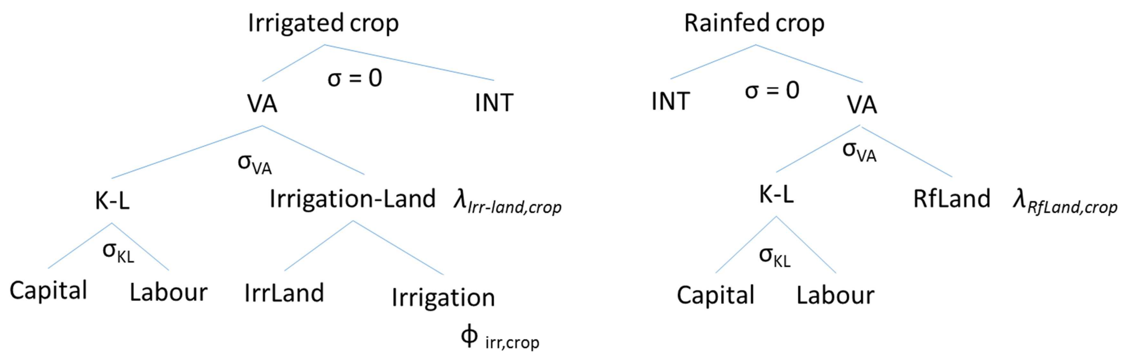
To simulate irrigation water requirements in the 2004-2050 time horizon, we use the RESCU model which is a global recursive-dynamic model using the GTAP database for the base year calibration. It comprises 20 world regions and 24 sectors aggregated from the 140 countries and 57 sectors present in the GTAP9 database (see Tables S1 and S2 in Supplementary Material A). The regional aggregation was done to reflect differences in growing conditions according to agro-ecological zoning and water availability.

2.2.1. Crop production functions

The model details irrigated and rainfed production distinctly for the eight crop classes represented. Both production functions assume a Leontief nest (perfect complements) between value-added *VA* and the intermediate goods bundle *INT* - Figure 2. For irrigated production, value added *VA* is a Constant Elasticity of Substitution (CES) nest composed of the *Irrigation-Land* the capital-labour *KL* bundles. *Irrigation-Land* is a Leontief composite of irrigable land *IrrLand* and *Irrigation.* The zero substitution elasticity σ_{IRR} assumption in *Irrigation* stems from the consideration that without irrigation water, irrigable land can no longer provide the same yields as initially assumed. In the rainfed production nesting, the *Irrigation-Land* bundle is replaced by rainfed land *RfLand*, allowing for substitution between this factor and the capital-labour *KL* composite. The exogenous expected yield improvements derived from the IMPACT model data [43] for a medium GDP and population growth scenario are applied to the productivity parameters of *Irrigation-Land* ($\lambda_{IrrLand,crop}$) for irrigated crops and to those of *RfLand* ($\lambda_{RfLand,crop}$) for rainfed crops.

The *Irrigation* factor in each crop production function has an associated blue water intensity $\phi_{irr,crop}$ which is specific to each crop type. Therefore considering that *Irrigation* is a fully mobile factor, the move of its use from one crop production to another would lead to different irrigation water requirements depending on the differences between crop water intensities.

Figure 2 – RESCU Irrigated and rainfed crop production functions



Compared to the other global CGE models covering freshwater as a distinct factor of production, RESCU further specifies crop production nesting. In the GTAP-W and GTAP-BIO-W models, all land types were bundled with capital, labour and energy[1], allowing for direct substitution between any pair of factors. The isolation of the capital-labour substitution in the RESCU model is based on the assumption that

[1] Both GTAP-W and GTAP-BIO-W are an evolution of the energy and environment GTAP-E model [59]

agricultural intensification, especially when moving to modern agricultural practices, implies a shift from labour to capital use. Furthermore, the labour and capital interaction is also of a particular interest in the present research, bearing in mind that capital and labour supply have different dynamics in the socioeconomic pathways considered.

2.2.2. Base year irrigation valuation

Irrigation is not recognised as a component of value added in national input-output accounts, and therefore the GTAP database does not directly provide the value information for this factor in the base year. Nevertheless, in a global modelling setting, it is tipically assumed that the value of irrigation can be derived from that of irrigated land i.e. irrigation improves crop yields and this is then reflected in higher rents of irrigated land. As detailed in Supplementary Material B, we introduce an improved valuation method in which we relate the value of irrigation water to the production losses when irrigation does not occur. This is done by using the crop production and yield change information determined by the 'no irrigation' scenario of the GCWM model [44].

2.2.3. Factor supply

The model comprises six factors of production - capital, labour, pasture land, rainfed land, irrigable land and irrigation. The supply of the former three is specified exogenously. *Pasture land*[2] is considered to be fixed throughout the simulation horizon, whereas *capital* and *labour* are changed given socio-economic development – capital stock follows investment and depreciation while labour is adjusted based on the evolution of the 15-65 years age groups within each region. As the base year comprises investment levels in developing regions that are high and unlikely for the long run notably, investment shares are being adjusted following the dynamics determined by the macro-econometric MaGE model [45] for each SSP considered. Also, a labour productivity factor is endogenised in order to meet the annual GDP growth targets in the model simulations. It is assumed that labour productivity in agricultural activities is lower than that of other sectors. Hence gains here are half those of non-primary sectors.

Rainfed and *irrigable land* are supplied through a two-stage mechanism. In the first stage, total available arable land supply for each region $Aland_r$ is specified using a logistic function:

$$\boldsymbol{ALand_r = \frac{LandMax_r}{1+\varepsilon_r e^{kland\frac{PALand_r}{PINDEX_r}}}} \qquad \textbf{\textit{(1)}}$$

The function is calibrated by an upper arable land expansion limit *LandMax*$_r$ derived from the GAEZ database [46]. The ε_r parameter is used to shift the sigmoid supply curve to the equilibrium point in the base year. The *kland* parameter determines the steepness of the supply curve. A value of 0.02 was chosen in all regions which leads to an initial land supply elasticity in the range of 0.33-1.87% depending on the size of *LandMax*$_r$ in each region. In this research, *LandMax*$_r$ excludes land obtained through deforestation. The availability of cropland thus reacts to market prices – when the price of land *PALand* exceeds the regional price index *PINDEX*, additional supply is brought in to counter price inflation. In a second stage, crop land is split into rainfed and irrigated land using a CET function. Given that there are no estimates of the transformation elasticities for the two land types at national or regional levels, the CET function is calibrated by assuming an elasticity of 2. The choice of this value is made to indicate a moderate ease of conversion from one type of land to another[3]. Nevertheless, the impact of altering this assumed value does not change the model results significantly (see sensitivity analysis in Supplementary Information).

The supply of irrigation is driven by its price *PIrr* relative to the regional price index through a logistic function similar to that of arable land:

[2] Non-crop land serves as an input only to livestock after the RESCU land disaggregation

[3] We use a lower value than in GTAP-BIO-W [60] where a value of 10 is employed

$$Irrigation_r = \frac{IrrMax_r}{1+\varepsilon_r e^{kirr\frac{PIrr_r}{PINDEX_r}}} \quad (2)$$

We follow the observation that an upper physical limit for freshwater withdrawals cannot be established due to the large reserves of groundwater[4] and the lack of information on freshwater uses in other sectors. Therefore considering the Leontief (no substitution) nesting of irrigable land (*IrrLand*) and irrigation, the supply of *Irrigation* is calibrated to follow the changes in available arable land such that this would not impose a significant constraint on the expansion or contraction of the *Irrigation-Land* bundle demand[5]. This is done by setting *IrrMax* to a value higher than *LandMax* for every region.

2.2.4. Agent behaviour

In line with standard specifications of CGE models, firms are profit maximising price takers and households are utility maximising agents subject to the disposable income balance. Final domestic demand is split between households, government and investment, each with a distinct spending function. Households choose their consumption basket based on a linear expenditure system (LES). The utility function thus comprises a subsistence component for each consumer good which is calibrated using the income and own-price elasticities of demand from the GTAP database. Subsistence levels are updated to track population changes throughout the simulation horizon. Government and the investment sector use Leontief demand functions (fixed shares) subject to total tax revenues and household savings respectively.

The aggregated domestic demand by commodity is met by domestic production and imports. For international trade, the RESCU model incorporates the Armington assumption [47] in which foreign and domestic varieties are regarded as imperfect substitutes.

2.2.5. Irrigation water requirements

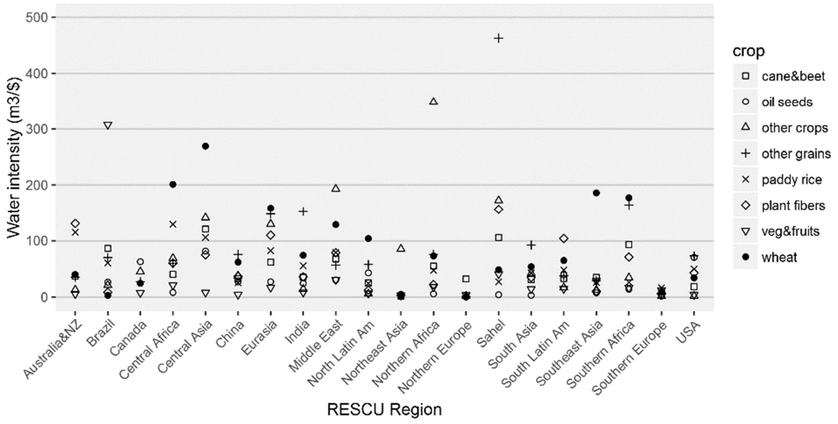
The inclusion of irrigation as a distinct input to production allows for an accounting of irrigation water requirements that tracks the changes in crop output and substitution effects between factors of production. Requirements for each crop class within a region are determined by multiplying the RESCU *Irrigation* factor uses by a blue water intensity coefficient $\phi_{crop,r}$ which is both region and crop specific (Figure 3). Total requirements within a region are thus calculated using the summation:

$$\boldsymbol{Irrigation\ water\ requirements_r = \frac{\sum_{crop,r} \Phi_{crop,r} Irrigation_{crop,r}}{\eta_r}} \quad \textit{(3)}$$

Here η_r represents the regional irrigation efficiency which includes field application and conveyance losses. We calculate efficiency rates for each RESCU region by following the procedure and irrigation country data from Rohwer et al.[48]. The obtained overall values range from 38% to 86% depending on the conveyance method and the technological mix of irrigation within each region.

[4] 10,530,000 km^3 groundwater reserves compared to 42,000 km^3 renewable freshwater resources [61]
[5] This is observed in model simulations without yield changes embedded where price differentials of *IrrLand* and *IrrWater* are negligible

Figure 3 - Blue water intensities of irrigation water value added - by crop and by region

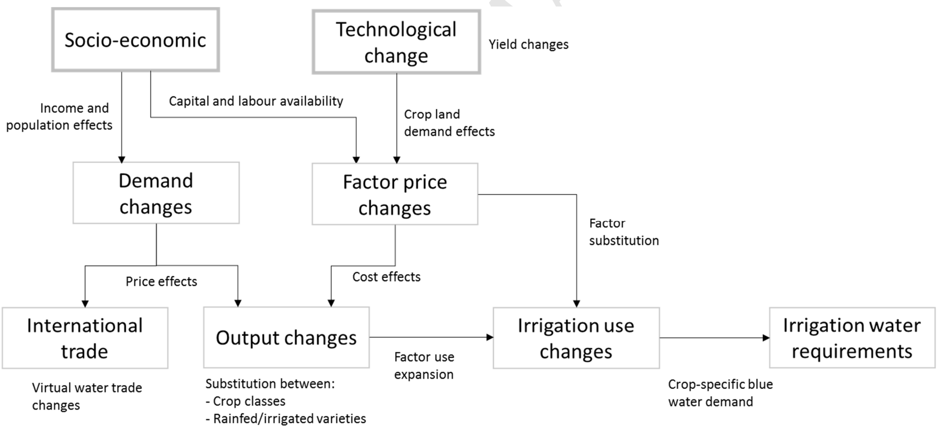


Source: GTAP RESCU database

2.2.6. Expansion mechanisms of irrigation water use

Starting from the two main drivers – socio-economic development and technological change - modifications in total water requirements can occur through multiple channels (Figure 4). We distinguish between a 'scale' effect determined by changes in the output of irrigated crops and a 'substitution' effect determined by factor substitution within crop production functions and between crop types.

Figure 4 - Mechanisms of changes in withdrawals



Source: own compilation

For the 'scale' effect, income and population growth lead to higher overall demand for crops given the household LES utility function and the underlying commodity income elasticities. These changes in demand are met either by domestic supply or through international trade. Given the CGE market clearing and zero economic profit conditions, changes in labour and capital stock availability induced by socio-economic evolution also have a scale impact over domestic supply through changes in costs of domestic production.

Relative price changes of production factors lead to a 'substitution' effect between inputs as suggested by the elasticities in the nested production functions from Figure 2. At the same time, the *Irrigation-Land* and rainfed land productivity changes ($\lambda_{Irr\text{-}Land,crop}$ and $\lambda_{RfLand,crop}$ respectively) through inherent yield changes differentiated by crop class have an impact on crop production costs. Hence, a substitution between crop classes and also between the irrigated and rainfed varieties within the same crop class can occur based on cost advantages of one commodity over the other. These changes in the crop production mix determine a reallocation of irrigation across crop types and ultimately lead to changes in water requirements.

2.2.7. Irrigation Withdrawals to Availability indicator

To measure the evolution of pressure coming from irrigated crop production we introduce the Irrigation Withdrawals to Availability (IWA) indicator. The indicator is a measure of total water requirements relative to Total Renewable Water Resources (TRWR) in each RESCU region:

$$\boldsymbol{IWA_r} = \frac{\boldsymbol{Irrigation\ water\ requirements_r}}{\boldsymbol{TRWR_r}} \tag{4}$$

TRWR for each country represents the sum of all internal resources and that of all inflows from its neighbours. To correct the double counting issue coming from river basins being shared by several countries within a region, we determine the TRWR values at a regional level by taking into account only inflows between regions and not within regions. The values taken into account are outlined in Table S4 in Supplementary Material A.

In line with the Withdrawals to Availability (WTA) indicator introduced in Alcamo et al.[49] and the Water Stress Index (WSI) from Fischer et al.[50], we set an IWA threshold of IWA ≥ 0.2 for medium pressure and IWA ≥ 0.4 for severe pressure of irrigation withdrawals exerted over available renewable resources.

2.3. Alternative futures scenarios

The irrigation requirements and IWA values are determined for three future scenarios taken from [2] - SSP1 “Sustainability”, SSP2 “Middle of the Road” and SSP5 “Conventional Development”. A description of the selected futures is presented in Table S5 and Figure S1 in Supporting Information. It should be noted that SSP1 is labelled as the “sustainability” pathway from a greenhouse gas emissions perspective and not necessarily from that of all resources. Also, while the growth patterns assumed by these storylines are linked to carbon concentration outcomes, importantly these do not incorporate the possible feedback effect of climate change on socioeconomic development

In the RESCU model, the SSPs are implemented through GDP growth rates and demographic changes. GDP growth leads to an overall increase in demand of goods as total income rises whilst the demographic evolution has two distinct consequences. On one hand, the subsistence consumption component of the LES utility function expands due to population growth. On the other hand, the supply of labour follows the changes in total active population stemming from a flattening of population growth by 2050. Downscaled socioeconomic data are taken from the IIASA SSP database[6]. For each future scenario, the derived growth rates of the relevant variables (real GDP, subsistence consumption, active population) are applied over the 2004-2050 horizon through annual simulation time steps.

3. Results

In order to explain the link between socioeconomic development and irrigation water requirements, we analyse the crop output evolution and the outcomes regarding irrigation use patterns across the eight crop classes. The impact of international trade over irrigation withdrawals and regional changes in pressure on renewable resources is also determined by tracing the flows of virtual water related to crop trade, i.e. the water requirements to produce the crops which are later exported.

3.1. Crop output

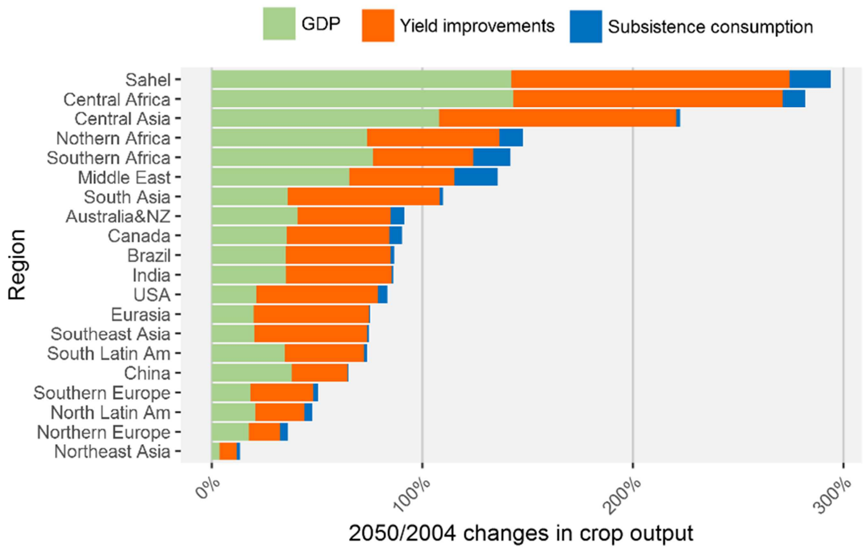
Crop output expands across all regions and virtually across all crop classes. Globally, crop production is projected to grow by 87.6% (SSP1), 83.2% (SSP2) and 101.1% (SSP5) by 2050 from 2004 values. At a

[6] https://tntcat.iiasa.ac.at/SspDb (accessed 16 September 2016)

regional level, total crop output growth ranges from 12% (Northeast Asia) to 294% (Sahel) in SSP2 (See Table S6 in Supplementary Material A). Higher output expansion takes place in regions with more pronounced socioeconomic development (Africa, Middle East, South Asia) and in those regions that are important crop exporters (Australia, USA). Irrigation production grows more than that on rainfed land across all regions mainly due to larger inherent yield improvements. Overall, irrigated agriculture increases its importance in world crop output, however, rainfed production continues to represent the larger share at a global level.

GDP growth and yield improvements have the highest impact on crop production in all regions (Figure 5). Income expansion leads to an increase in demand for crops, whilst yield improvements further boost this through a reduction in costs of production. Increases in subsistence consumption driven by population growth have a limited effect, however still visible in many regions. This is due to a significant expansion of disposable income which reduces the weight of subsistence spending in the overall household budget. Meeting the subsistence consumption becomes thus less of a constraint in the budget allocation across consumer goods.

Figure 5 - Decomposition of crop output growth 2050/2004 - SSP2. GDP and yield improvements are the main drivers generating crop output growth.



3.2. Projected irrigation water requirements

Global irrigation water requirements in 2050 are expected to reach 2605 km^3 (SSP1), 2583 km^3 (SSP2) and 2645 km^3 (SSP5) which is a 9.4%, 8.5% and 11.1% increase for SSP1, SSP2 and SSP5 respectively from 2004 levels. In most regions water withdrawals expand with changes in Central Africa, India, Sahel and Central Asia (Figure 6). In these regions, higher growth SSPs (SSP1 and SSP5) exacerbate the increases in water requirements. In cases where a decrease in irrigation water requirements occurs, the results are more mixed – higher global socioeconomic development further alleviates pressure from withdrawals in one group (Canada and China) but partially offsets this reduction for another group of regions (Southeast Asia, Eurasia and South Asia). The differences between these two groups are dictated by the relative sizes of the 'scale' and 'substitution' effects as outlined in Section 2.2.6.

The obtained increases in irrigation requirements have a significant impact over already water-challenged regions. Irrigation pressure continues to grow in regions with an IWA over 20% in the base year. The metric reaches values of 88-92% in Northern Africa, 64-68% in the Middle East (**Table 1**). India enters the high pressure domain with a projected IWA of 42-43% in 2050. Furthermore, Central Asia faces significant increases in the IWA values across the SSP scenarios and hence in SSP5 goes beyond the 20% stress threshold for medium pressure. South Asia is the only one in which irrigation water requirements are comparable to 2004 levels. However, the IWA of over 100% suggests continued river basin over-exploitation across the region. These increases in water requirements if translated into actual withdrawals will further deteriorate the irrigation water stress map across a wide geographical area spanning from Northern Africa to Central Asia (see Figure S3 in Supplementary Material A).

Figure 6 - Regional irrigation withdrawal changes 2004/2050. Most regions increase the irrigation water requirements. Decreases occur in areas in which yield improvements lead to a substitution to rainfed crop varieties and less-water intensive crop classes.

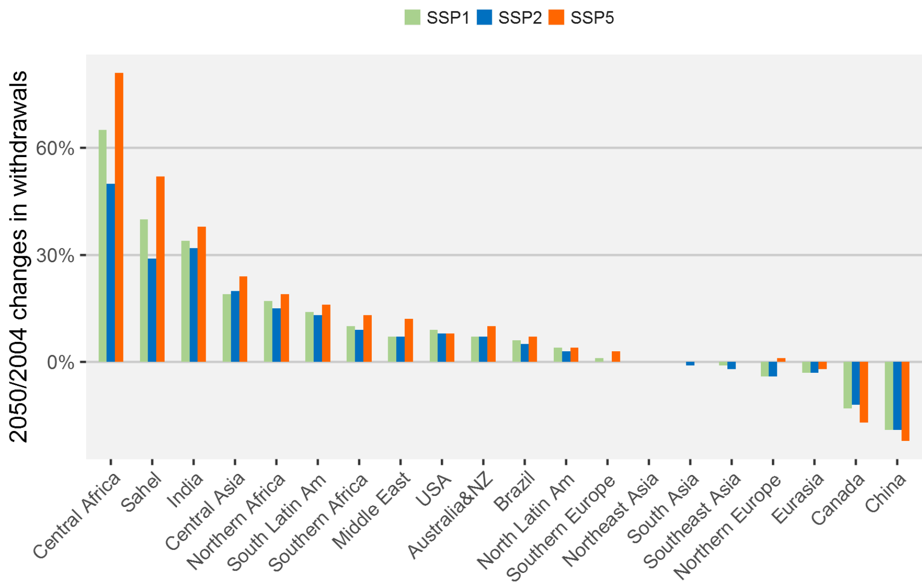


Table 1 – IWA in 2004 and 2050 by SSP

Region	2004	2050		
		SSP1	SSP2	SSP5
South Asia →	103.89%	103.56%	102.78%	103.96%
Northern Africa ↗	76.80%	89.70%	88.43%	91.75%
Middle East ↗	58.17%	62.17%	62.38%	64.93%
India ↗	31.61%	42.32%	41.68%	43.49%
Central Asia ↗	16.41%	19.59%	19.75%	20.31%
China ↘	12.86%	10.38%	10.45%	10.07%
USA ↗	7.58%	8.24%	8.20%	8.16%
Southern Europe ↗	7.13%	7.18%	7.15%	7.32%
Southern Africa ↗	5.55%	6.12%	6.06%	6.26%
Southeast Asia ↘	2.91%	2.87%	2.84%	2.90%
Australia&NZ ↗	1.78%	1.91%	1.89%	1.96%
Northeast Asia →	1.84%	1.84%	1.84%	1.84%
North Latin Am ↗	1.37%	1.43%	1.42%	1.43%
South Latin Am ↗	1.08%	1.23%	1.23%	1.26%
Sahel ↗	0.78%	1.09%	1.00%	1.18%
Central Africa ↗	0.61%	1.01%	0.92%	1.11%
Eurasia ↘	0.43%	0.42%	0.42%	0.42%
Brazil ↗	0.13%	0.14%	0.14%	0.14%
Northern Europe ↘	0.07%	0.07%	0.07%	0.07%
Canada →	0.07%	0.06%	0.07%	0.06%

3.3. Irrigation supply and allocation

If the 'scale' effect of socioeconomic development over irrigation withdrawals is highlighted by the general crop output expansion, the 'substitution' effect is determined by changes in factor allocation across time given relative yield improvements and factor availability modifications. This leads to alterations in the way irrigation is used across the eight crop classes and implicitly determines changes in withdrawals given the differences in blue water intensities between crop classes.

In SPP2, the supply of irrigation increases 9.0% globally by 2050 for SSP2 (Table 2) with a variation across regions ranging from -1.0% (Northeast Asia) to 104.2% (Central Africa). In addition to this overall growth, there is a re-allocation of irrigation uses between crops. Wheat production in India nearly doubles the use of irrigation water determining the single most important increase in withdrawals. The increase is only slightly offset by reductions in irrigation of other crops (plant fibers, oil seeds and other crops). For China, despite an overall increase of 13.5% in irrigation supply, total water withdrawals decrease. Irrigation here is re-allocated away from cereals (wheat, paddy rice and other grains) to less water-intensive crops for this region (vegetables&fruits, cane&beet) lowering the withdrawal impact of the overall use of irrigation. Globally, changes in irrigation use patterns lead to significant withdrawal increases for wheat (coming mainly from India and Central Asia), vegetables&fruits (China, India, South Asia, Middle East, Southeast Asia), and decreases for paddy rice (China, Southeast Asia) and plant fibers (India, Central Asia).

3.4. Virtual water flows through international trade

Global flows of virtual water expand from 255 **km^3** in 2004 to 288 **km^3** (SSP1), 282 **km^3** (SSP2) and 296 **km^3** (SSP5) in 2050. Some regions make considerable savings on the own irrigation water requirements through international trade (Figure 7) either by reducing the export of water-intensive crops (Central Asia) or by increasing imports (Nothern Africa, India, China). On the other side of the spectrum, more withdrawals are determined by the export of more crops (South Asia, USA) and through fewer imports complemented by an increase in domestic production (Middle East).

The analysis of virtual water flows shows that water stressed regions are exporting considerable volumes of water and many continue to do so in the future (Figure 8). In South Asia, exports of crops (notably vegetables&fruits to India) become an important weight in withdrawals by 2050 (6% of TRWR). Therefore, in this region, the reduction in withdrawals coming from the reallocation of irrigation across crops on the supply side is offset by the growth in net virtual water exports. At the same time, although important exporters initially, the Middle East and Northern Africa see a reduction in exports of virtual water across all destination regions.

It should be noted that at a regional level these virtual water flow changes do not necessarily imply modifications in the same direction of total physical flows of crops. With different water intensities depending on the crop class and the production region, an overall change in virtual water exports may be coming from changes in the structure of exported crops. Although volumes of trade in crops may be of interest from a food security perspective, these fall outside the scope of this paper.

Figure 7 - Net trade of crop virtual water 2004 and 2050 – SSP2. A few regions make savings on irrigation withdrawals by increasing virtual water imports or by reducing exports.

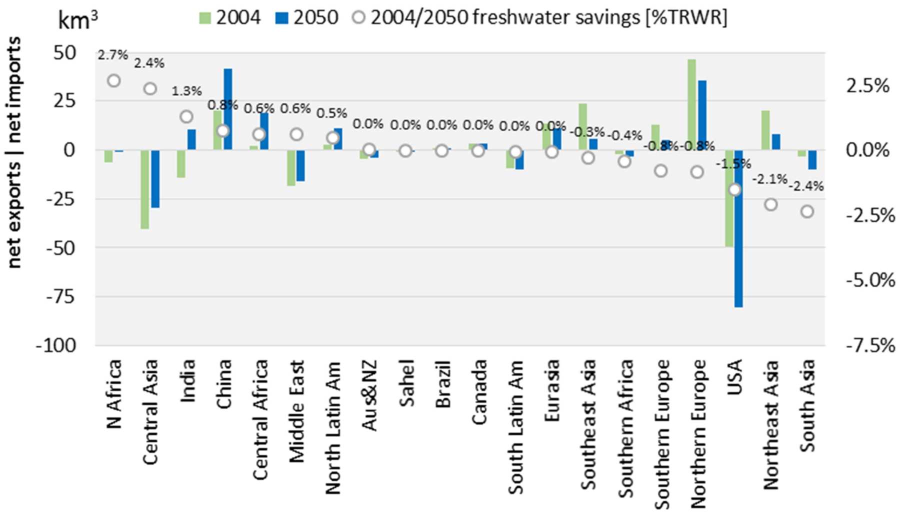


Figure 8 - Virtual water flows in 2004 (255 km³) and 2050 (288 km³). The arrows show the exporter to importer direction of flows. Flows within a region are determined by trade between countries belonging to the same RESCU region.

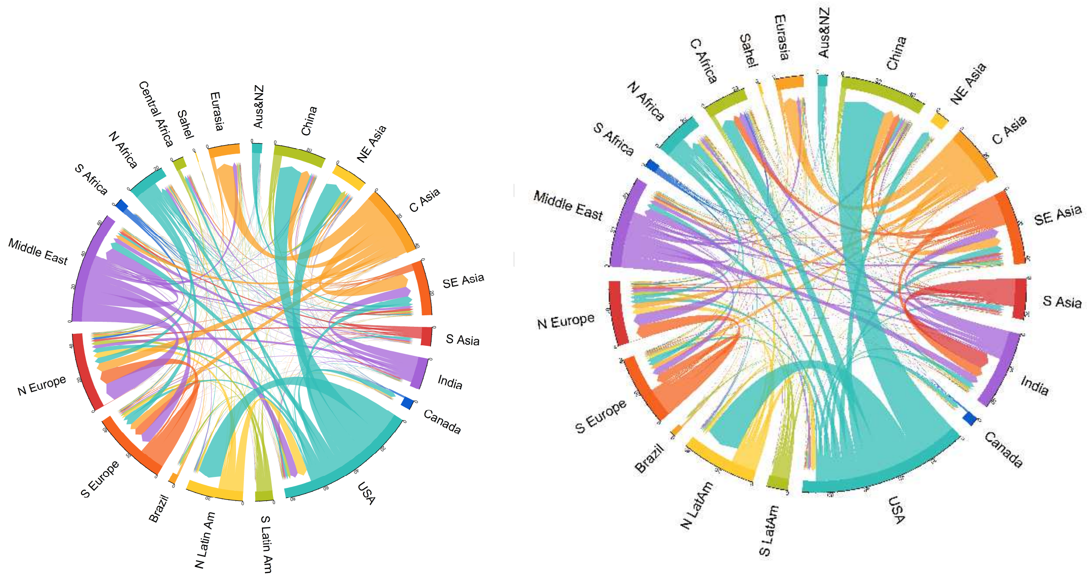


Table 2- Changes in irrigation uses and withdrawals 2004/2050 - SSP2. Depending on the allocation of irrigation across crop classes, changes in irrigation use and water requirements can move in different directions. The largest changes in water requirements occur in regions with extensive irrigation.

	Changes in irrigation water requirements (km^3)									Changes in irrigation use (%)								
	wheat	paddy rice	other grains	veg&fruits	plant fibres	cane&beet	oil seeds	other crops	**overall**	wheat	paddy rice	other grains	veg&fruits	plant fibres	cane&beet	oil seeds	other crops	**overall**
Australia&NZ	0.01	1.42	0.14	-0.05	-1.08	-0.08	0.00	0.59	**0.95**	2%	79%	19%	-2%	-24%	-2%	10%	43%	**6%**
Brazil	0.00	0.33	-0.02	0.36	-0.01	-0.26	0.08	0.04	**0.53**	14%	7%	-13%	14%	-8%	-14%	71%	3%	**4%**
Sahel	-0.06	-0.33	-0.09	0.75	-0.06	0.52	0.00	1.57	**2.31**	-26%	-7%	-32%	62%	-60%	63%	101%	184%	**38%**
Central Africa	-0.09	1.77	-0.29	5.78	-0.50	-1.55	-0.12	3.02	**8.01**	-99%	24%	-34%	305%	-73%	-85%	-91%	99%	**104%**
Central Asia	10.55	1.31	9.26	4.43	-7.90	0.32	0.00	-3.20	**14.79**	220%	29%	148%	58%	-19%	71%	1%	-47%	**28%**
China	-23.36	-47.05	-15.58	20.63	-3.83	2.39	0.80	-3.82	**-69.82**	-38%	-23%	-29%	109%	-50%	73%	6%	-90%	**13%**
Eurasia	-1.06	-0.14	-0.93	0.29	0.19	-0.16	0.11	1.06	**-0.62**	-17%	-10%	-20%	10%	19%	-21%	50%	35%	**2%**
India	178.70	32.84	-10.17	6.63	-10.32	-3.49	-11.75	8.49	**190.94**	94%	16%	-67%	20%	-36%	-4%	-70%	29%	**21%**
Middle East	-5.52	-1.07	2.17	14.65	2.05	-0.22	1.02	4.25	**17.33**	-14%	-6%	12%	17%	10%	-2%	34%	10%	**12%**
Northern Africa	-6.53	5.44	-10.68	4.58	3.39	4.21	0.32	24.43	**25.17**	-28%	34%	-43%	10%	44%	36%	27%	70%	**11%**
Northeast Asia	0.00	-0.10	-0.04	-0.01	0.00	0.00	0.13	0.02	**0.00**	5%	-1%	-24%	-5%	27%	-8%	96%	9%	**-1%**
Northern Europe	0.00	0.00	0.00	-0.09	0.00	0.04	0.00	0.02	**-0.04**	-22%	86%	-21%	-18%	20%	18%	-31%	9%	**4%**
North Latin Am	2.92	-0.81	-2.99	1.22	0.65	1.10	1.04	0.06	**3.18**	27%	-7%	-23%	4%	23%	6%	108%	1%	**3%**
Canada	-0.17	0.00	-0.11	0.12	0.00	0.00	0.01	-0.11	**-0.27**	-29%	24%	-28%	48%	20%	-1%	1%	-23%	**4%**
Southern Africa	-0.10	0.03	0.57	0.68	0.27	-0.59	-0.12	0.31	**1.04**	-6%	28%	73%	21%	32%	-25%	-61%	15%	**13%**
South Asia	-33.07	7.01	5.81	20.63	-1.25	1.70	-0.18	-3.86	**-3.21**	-28%	12%	44%	147%	-3%	7%	-11%	-15%	**9%**
Southeast Asia	8.48	-44.43	-1.37	28.45	-0.04	-1.92	-0.18	6.58	**-4.44**	80%	-28%	-75%	290%	-30%	-16%	-19%	144%	**9%**
Southern Europe	-0.23	0.50	-1.21	-0.37	1.15	0.13	0.84	-0.64	**0.17**	-12%	13%	-10%	-1%	22%	6%	28%	-7%	**0%**
South Latin Am	0.33	0.12	0.88	-0.27	0.12	0.56	1.46	-0.50	**2.69**	37%	4%	60%	-3%	32%	37%	258%	-19%	**5%**
USA	2.73	6.16	-6.18	2.07	0.21	0.02	8.68	-0.70	**12.99**	23%	35%	-13%	8%	1%	1%	47%	-8%	**2%**
World	**133.54**	**-36.99**	**-30.83**	**110.47**	**-16.95**	**2.73**	**2.15**	**37.61**	**201.72**	**22%**	**-9%**	**-13%**	**30%**	**1%**	**1%**	**7%**	**1%**	**9%**

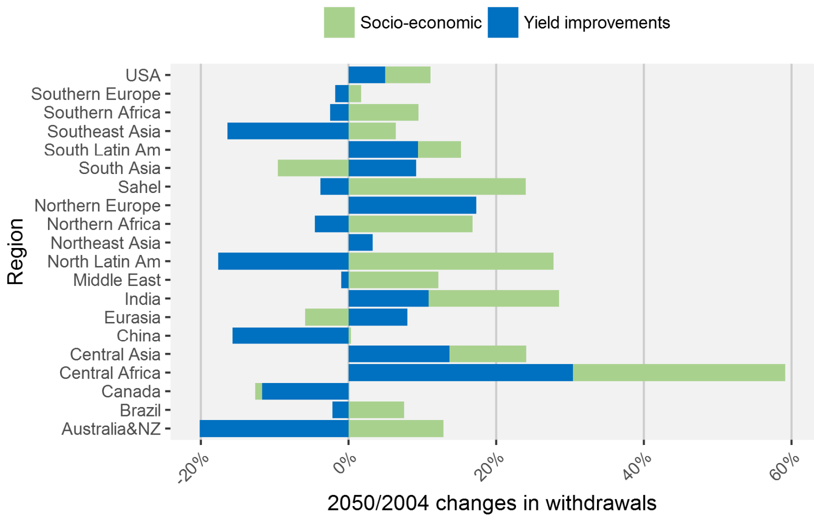
4. Discussion

4.1. Importance of socioeconomic drivers and yield changes

Socioeconomic development impacts the withdrawal levels in a significant way. The results are more pronounced in scenarios with higher economic growth for developing economies (SSP1 and SSP5), indicating the importance of the relationship between income and pressure over freshwater resources for these regions. Furthermore, whilst growth in irrigation use can be explained to a large extent by increases in domestic demand for crops, changes in exports can also have a visible impact on irrigation water requirements. Hence, some regions face strong virtual water export increases due to growth in demand elsewhere (e.g. vegetables&fruits from Southeast Asia and South Asia to India).

From a technological change perspective, yield improvements are equally an important driver in determining withdrawal levels (**Figure 9**). In the model, increases in yields lead to a reduction in land and irrigation demand in most regions (e.g. Central Africa, Northern Africa, Middle East). However, in some cases, the resulting cost reductions determine a rebound effect by further stimulating demand for irrigated crops and implicitly that for irrigation water (India, Sahel, South Asia). In China, the relative changes in yields between rainfed and irrigated varieties are the main factor leading to the considerable reduction in irrigation withdrawals.

Figure 9 - Contribution of socioeconomic drivers and yields to overall water requirements changes from 2004 to 2050. Socio-economic development is largely an enhancer of water requirements growth, whereas yield improvements can both increase and decrease requirements depending on irrigation allocation across crop classes.



4.2. Comparison to other recent assessments

The obtained results of an 8.5-11.0% increase in global freshwater withdrawals are situated within the range obtained from other studies. The expert judgement in Bruinsma [51] which determines a 70% increase in agricultural output globally, leads to an 11% increase in withdrawals. The outlook in Alexandratos & Bruinsma [1] gives a 6% increase for withdrawals in 2050 from 2005/2007 levels. The higher absolute values obtained (2761 km^3 initially and 2926 km^3 in 2050) comprise some categories which are not considered in this paper (irrigation of pasture land and the flooding of paddy rice). At the same time, the lower increases in withdrawal may be explained by the use of a conservative scenario for socio-economic development. As an underlying metric to withdrawals, Nelson et al. [43] obtain increases in beneficial water consumption over the 2010-2050 horizon by 17.2-28.1% and 7.9-18.0% for a set of SRES pathways with and without irrigation efficiency gains respectively. Further on, the IMPACT irrigation withdrawal results for SSP2 and no climate change incidence show a 15.9% increase in 2050 from 2005[7].

At a regional level, these assessments generally present an increase in irrigation withdrawals across developing economies. Therefore, we obtain similar trends for Northern Africa, Central Africa, Middle East, India and Latin America but opposing results for China and South Asia. The reduction in irrigation water for China is also obtained by IMPACT for the SSP2 scenario with comparable irrigation allocation across crops. For industrialised regions, expert judgement leads to a significant decrease in withdrawals. In contrast, IMPACT blue water uses increase in regions with extensive irrigation e.g. USA, similarly to our results. We can thus observe that studies which are reliant on expert judgment tend to have a more uniform effect of socioeconomic development over withdrawals, whereas modelled projections may lead to opposing effects among regions with similar prospects of development.

Compared to the IMPACT SSP2 results, the most important discrepancies observed for water-stressed regions refer to the allocation of blue water across crops in India and withdrawal trends in South Asia. For India, we obtain an increase in withdrawals for wheat complemented by decreases for other crops, whereas IMPACT obtains a more balanced increase across all crop classes. In South Asia, a marked decrease in wheat blue water use is also obtained, however, in IMPACT the growth for all other crops overcompensates for this which is leading to an overall expansion in demand for irrigation water.

4.3. Limitations and uncertainties

CGE results can only provide macro-regional averages as opposed to spatially-detailed models. The IWA indicator thus presents the trends of irrigation pressure from a global perspective whilst adding the market signals for factor allocation and international trade that spatially-detailed models are not able to embed. Hence, even within regions that appear to have enough resources to meet the future demand for irrigation water, there may be areas that will suffer from increased stress. These areas can be entire countries which are currently bundled in macro-regions in the disaggregated GTAP database (e.g. Mauritania, Niger), or river basins within large countries (e.g. North of China, West of Brazil, the Murray-Darling basin in Australia).

The irrigation withdrawal results in this paper are only constrained by the irrigation factor supply function which takes a logistic form. Therefore further work needs to be undertaken to endogenise withdrawals coming from other sectors (livestock, industry, households) to obtain an overall view over freshwater abstractions and to determine irrigation uses when considering an absolute regional withdrawal limit. Other CGE models have focused on irrigation supply changes stemming from withdrawals of non-crop sectors specified exogenously. Therefore these models do not yet have a consistent economy-wide representation of withdrawal changes coming from socio-economic development. In future development of the RESCU model, we will seek to include all major freshwater users and implement allocation mechanisms where withdrawals exceed available renewable resources.

Some uncertainty for withdrawal results can be attributed to the manner that yield improvements are implemented in the production function of irrigated crops. Whilst yield improvements mean less land required for the same amount of output, it is not clear from the crop modelling literature whether this would also imply lower water requirements. Furthermore, farm-level studies show that there is a trade-off between yield and water productivity (see Cassman et al. [52]), i.e. a subunitary but positive elasticity

[7] Obtained from the IMPACT model portal - http://impact-model.ifpri.org/#scenario/SSP2_NoCCwater/outputs/noncommodity (accessed 16 September 2016)

of yield to water application. Therefore, for developing regions, we cannot ascertain that closing down the observed yield gaps will not imply additional irrigation water per hectare. This is even less clear for industrialised regions in which higher yields will come from further R&D with possibly unknown implications over beneficial water use. For the time being, the RESCU model assumes that yield improvements on irrigated land impact both land and water inputs in the same way, however, more research should be dedicated to modelling yield as a function of water input.

The yield changes applied reflect inherent productivity gains and rule out climate change effects. Hence, by using multiple future scenarios to address the range of possible socioeconomic development pathways, we have sought to isolate the contribution of income and population growth to changes in irrigation withdrawals pressure under perfect mitigation conditions and expected technological advances. There is high uncertainty with regard to climate change incidence over local-level mean climatic conditions and yields (see for instance Nelson et al. [53] and Schewe et al. [54]). Therefore, we leave this topic for a separate analysis which would be required to cover the implications of climate-induced yield changes over crop output, freshwater withdrawals and GDP growth as deviations from the patterns described by the SSPs.

5. Conclusions

In this paper, we considered the evolution of resource pressure coming from blue water use in crop production at a global level using a bottom-up approach. Annual withdrawals up to 2050 were determined across a range of socioeconomic development pathways complemented by expected inherent yield changes. For this purpose, we employed the dynamic CGE model RESCU which uses an improved accounting methodology to derive the value of irrigation water as a distinct factor of production. The model also comprises a separate representation of irrigated and rainfed crop production functions to allow for a better specification of yield improvements of the two land types involved. Thus, from a water withdrawals perspective, the effects captured comprise an overall change in irrigation demand stemming from crop demand expansion but also importantly a substitution effect between the rainfed and irrigated varieties given yield differentials.

Throughout the 2004-2050 time frame, we obtained an increase in withdrawals at a global level across all three SSP scenarios considered. The largest withdrawal changes will occur in developing regions (Central Africa, India, Northern Africa, Middle East) but also major crop producers and exporters, e.g. the USA. Regions that are already water-stressed will maintain and even expand their pressure causing potential bottlenecks, especially where other sectors may compete for these resources. New areas (Central Asia) pass the IWA 20% threshold for stress. China is the only region with extensive irrigation that sees a considerable decrease in blue water uses as a consequence of changes in the crop production mix in the region.

The SSPs with higher income growth for developing regions (SSP1 and SSP5) produce larger withdrawal results. Therefore, SSP1, although labelled as the 'sustainability' pathway, leads to more pressure from irrigation than the ‘middle of the road’ SSP2. These findings highlight the relationship between income and water uses in agriculture hinting towards the need for more efforts to improve irrigation water efficiency in crop production in order to determine a more sustainable use of freshwater resources.

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Supplementary Material A

A1. Model configuration

Table S1. RESCU-GTAP regional aggregation

RESCU region	GTAP9 countries
AUZ – Australia and New Zeeland	Australia, New Zeeland, Rest of Oceania
SEA – South East Asia	Brunei, Cambodia, Indonesia, Laos, Myanmar, Philippines, Singapore, Thailand, Vietnam, Nepal, Rest of SE Asia
CNA- China	China, Hong Kong, Taiwan
NEA – North East Asia	Japan, Korea Republic of, Rest of East Asia
SAS – South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia
IND – India	India
CEA – Central Asia	Mongolia, Kazakhstan, Kirgizstan
MEA – Middle East Asia	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, UAE, Rest of Western Asia*
EUA – Eurasia	Belarus, Russia, Ukraine, Rest of Eastern Europe, Rest of Former Soviet Union*, Armenia, Azerbaijan, Georgia
NEU – Northern Europe	Belgium, Denmark, Estonia, Finland, Germany, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Sweden, Great Britain, Switzerland, Rest of EFTA*
SEU – Southern Europe	Austria, Cyprus, Czech Republic, France, Greece, Hungary, Italy, Malta, Portugal, Slovakia, Slovenia, Spain, Albania, Bulgaria, Croatia, Romania, Rest of Europe*
NAF – Northern Africa	Egypt, Morocco, Tunisia, Rest of North Africa*, Rest of Eastern Africa*
CAFH – Central Africa Humid	Benin, Burkina-Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Togo, South Central Africa*, Ethiopia, Kenya, Madagascar, Mauritius, Mozambique, Rwanda, Tanzania, Uganda
CAFD – Central Africa Dry	Rest of Western Africa*, Rest of Central Africa*, Senegal
SAF – Southern Africa	Malawi, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of South African Customs Union*
NOA – Canada	Canada, Rest of North America*
USA – United States	United States
NLAM – North Latin America	Mexico, Bolivia, Columbia, Ecuador, Peru, Venezuela, Rest of South America*, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America*, Dominican Republic, Jamaica, Puerto Rico, Trinidad Tobago, Caribbean*
BRA – Brazil	Brazil
SLAM – South Latin America	Argentina, Chile, Paraguay, Uruguay, Rest of the World*

Table S2. RESCU-GTAP sectoral aggregation

RESCU sector	**GTAP 9 sector**
PDR_IRR – paddy rice irrigated	PDR
PDR_RFC – paddy rice rainfed	
WHT_IRR – wheat rice irrigated	WHT
WHT_RFC – wheat rice rainfed	
GRO_IRR – other grains irrigated	GRO
GRO_RFC – other grains rainfed	
V_F_IRR – veg&fruits irrigated	V_F
V_F _RFC – veg&fruits rainfed	
OSD_IRR – oil seeds irrigated	OSD
OSD_RFC – oil seeds rainfed	
C_B_IRR – cane and beet irrigated	C_B
C_B_RFC – cane and beet rainfed	
PFB_IRR – plant fibres irrigated	PFB
PFB_RFC – plant fibres rainfed	
OCR_IRR – other crops irrigated	OCR
OCR_RFC – other crops rainfed	
LSTK – Livestock	CTL Cattle, OAP Animal products, RMK Raw milk, WOL wool
AGRO – Agriculture other	FRS forestry, FSH Fish
PCF – Processed food	OMT Meat products, VOL Vegetable oils, MIL Dairy products, PCR Processed rice, SGR Sugar, OFD Food products other, B_T Beverages and tobacco
MANU – mining and manufacturing	TEX Textiles, WEA Wearing apparel, LEA Leather products, LUM Wood products, PPP Paper products, OMN minerals, CMT cement, CRP chemicals, NMM mineral products, I_S iron and steel, NFM non-ferrous metals, FMP metal products, MVH motor vehicles, OTN transport equipment, ELE electric equipment, OME machinery, OMF manufactures, WTR water
SERV – Services	OSG Public Administration, CMN Communication, OFI Financial services, ISR Insurance, OBS Business services, ROS Recreational services
TRSP – Transport	OTP Transport, WTP Water Transport, ATP Air transport
CONS – Construction	CNS Construction, DWE Dwellings
ENE - Energy	COA coal, OIL oil, GAS gas, P_C petroleum coal, ELY Electricity, GDT gas distribution

Table S3. RESCU-GCWM crop mapping

RESCU crop class	GCWM crop class
PDR – paddy rice	Wheat (1)
WHT – wheat	Rice (3)
GRO – other grains	Maize (2), Barley (4), Rye (5), Millet (6), Sorghum (7)
V_F – vegetables and fruits	Potatoes (10), Cassava (11), Groundnuts (16), Citrus (18), Date palm (19), Grapes (20), Other perennial (24)
OSD – oil seeds	Soybeans (8), Sunflower (9), Oil palm (14), Rapeseed/canola (15)
C_B – cane and beet	Sugar cane (12), Sugar beet (13)
PFB – plant fibres	Cotton (21)
OCR – other crops	Pulses (17), Cocoa (22), Coffee (23), Others annual (26)
Not mapped	Managed grassland (25), Maize forage (27), Rye forage (28), Sorghum forage (29)

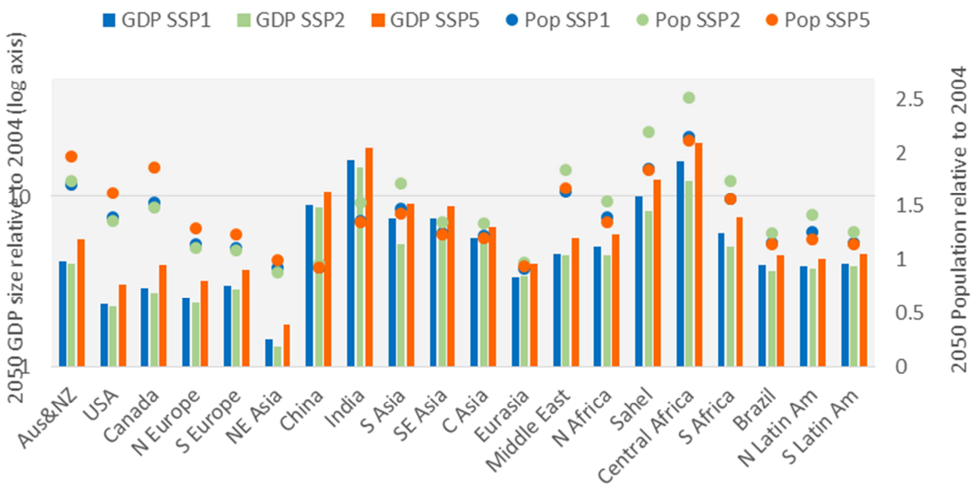
Table S4. TRWR estimation for RESCU regions in km^3. ATRWR, TRWR, IRWR values are taken from FAO [55], inflow values are taken from the country profile data from the FAOSTAT database. [1]country-level inflow data not available. [2]ATRWR values represent total actual renewable resources are determined by deducting the volumes included in water treaties from the total the TRWR metric.

Region	**Values considered**	**Total value (km^3)**
Canada	ATRWR	2902
USA	ATRWR / Alaska not considered	2089.4
Northern Latin America	IRWR + inflows: USA -> Mexico 5.4 km^3	6937.5+ 5.4 **=6942.9**
Brazil	ATRWR	8233
South Latin America	IRWR + inflows: Brazil -> Paraguay 73.3 km^3 Brazil -> Argentina 442.5 km^3 Brazil -> Uruguay 70 km^3 Bolivia -> Argentina 10.1 km^3 Bolivia->Paraguay 5.9 km^3	1269.2+ 601.8 **=1871**
Northern Europe	IRWR	1299.9
Southern Europe	IRWR + total inflows France 25.2 km^3 Italy 8.8 km^3 Austria 22.7 km^3	873.6+ 56.7 = **930.3**
Northern Africa	IRWR + total inflows: Sudan 119 km^3	97.3+ 119 =**216.3**
Sahel	IRWR[1]	**1039.2**
Central Africa	IRWR[1]	**2624.7**
Southern Africa	ATRWR for Zambia 105.2 km^3 IRWR for other + total inflows: Angola -> Namibia 10 km^3	105.2+ 89.6+ 10 =**204.8**
Middle East	IRWR + total inflows: Southern Europe ->Turkey 3.5 km^3 Afghanistan->Iran 6.7 km^3	411+ 10.2 =**412.2**
Central Asia	IRWR + total inflows: Russia -> Kazakhstan 9.2 km^3 China -> Kazakhstan 21.5 km^3 China -> Kyrgyzstan 0.5 km^3 Iran -> Turkemnistan 1.1 km^3	411+ 32.3 = **443.3**
Eurasia	IRWR + total inflows: China ->Russia 119 km^3 Turkey -> Armenia 9.9 km^3	4511.6+ 128.9 = **4640.5**
South Asia	IRWR for Pakistan ATRWR for Afghanistan[2] + total Pakistan inflows: 170 km^3 (Indus Treaty)	55+ 65+ 170 = **290**
India	ATRWR	**1896.7**
Southeast Asia	IRWR + total inflows: China -> Southeast Asia 217.8 km^3 India -> Bangladesh 1121.6 km^3	5349.2+ 1339.4 =6778.6
China	ATRWR	2896.6
Northeast Asia	ATRWR	561.85
Australia and New Zealand	ATRWR / Rest of Oceania excluded	819
Total		**42020.35**

Table S5. SSP pathway description

SSP scenario	Details
SSP1 – Sustainability	Rapid development of low-income countries, reduction of inequality between economies; globalised economy; reduced dependency on fossil fuels and reduced resource intensity; adoption of clean energy technologies awareness of environmental degradation Model implications: **high** GDP growth in developing countries and **medium** in developed countries, **medium** population growth
SSP2 – Middle of the Road	Same trends as in previous decades; disproportionate development of low-income economies; global income per capita increases at a medium pace; reduction of energy intensities; some decrease of dependency on fossil fuels Model implications: **medium** GDP growth, **high** population growth
SSP5 – Conventional Development	Orientation towards economic growth; energy systems dependent on fossil fuels; highly-engineered infrastructure Model implications: **high** GDP growth, **medium** population growth

Figure S1. Regional GDP and population growth in 2050 relative to 2004



A2. Additional results

Table S6. SSP2 crop output growth in 2050 relative to 2004

	wheat	paddy rice	other grains	veg& fruits	plant fibres	cane& beet	oil seeds	other crops	combined	irrigated	rainfed
Aus&NZ	81.4%	120.6%	75.1%	122.7%	111.4%	39.7%	21.1%	48.4%	**91.4%**	104.4%	80.1%
Brazil	131.0%	63.3%	50.8%	69.8%	120.8%	88.0%	129.5%	65.5%	**86.6%**	135.6%	78.4%
Sahel	54.6%	187.1%	346.8%	333.8%	175.5%	186.9%	248.1%	120.4%	**293.9%**	274.6%	297.0%
Central Africa	670.4%	283.8%	327.9%	324.8%	239.4%	232.9%	238.0%	124.5%	**281.9%**	586.3%	265.4%
Central Asia	239.6%	301.8%	324.2%	264.6%	129.4%	259.7%	110.9%	-25.0%	**222.5%**	237.6%	191.1%
China	15.7%	18.8%	106.4%	72.7%	197.4%	138.2%	33.8%	35.7%	**64.9%**	108.9%	39.8%
Eurasia	73.7%	94.0%	69.8%	72.4%	160.4%	99.6%	91.5%	99.3%	**75.3%**	95.2%	73.1%
India	222.7%	70.3%	303.1%	56.5%	114.3%	19.6%	89.3%	42.6%	**86.0%**	108.9%	71.6%
Middle East	129.4%	107.3%	153.2%	129.0%	206.6%	145.3%	204.0%	106.4%	**135.9%**	159.6%	100.5%
Northern Africa	177.6%	104.3%	95.6%	143.8%	213.5%	149.5%	120.0%	154.7%	**147.7%**	132.3%	178.5%
NE Asia	38.1%	2.4%	116.5%	16.2%	73.9%	1.2%	75.3%	14.2%	**12.0%**	8.4%	14.7%
Northern Europe	34.4%	158.6%	41.1%	18.8%	43.3%	57.9%	34.7%	43.9%	**36.2%**	49.6%	34.3%
Northern Latin Am	23.4%	46.3%	61.2%	49.8%	126.5%	93.2%	42.3%	19.9%	**47.9%**	60.5%	39.3%
Canada	97.5%	54.3%	76.5%	184.1%	57.0%	61.7%	59.0%	46.5%	**90.3%**	132.0%	84.8%
Southern Africa	260.2%	89.8%	186.4%	133.1%	143.2%	131.7%	87.4%	113.0%	**141.8%**	162.2%	118.6%
South Asia	30.8%	57.8%	156.0%	274.0%	73.3%	104.6%	158.6%	16.3%	**109.8%**	98.7%	172.0%
SE Asia	476.1%	24.9%	53.3%	139.6%	193.9%	37.8%	80.1%	33.5%	**74.4%**	110.2%	61.2%
Southern Europe	56.8%	67.3%	43.6%	27.4%	40.8%	86.5%	80.4%	58.8%	**50.5%**	73.9%	38.0%
Southern Latin Am	81.4%	53.7%	87.5%	49.6%	162.3%	91.1%	88.6%	25.3%	**73.9%**	93.5%	66.9%
USA	121.9%	133.1%	50.2%	82.0%	127.7%	43.0%	121.4%	73.1%	**83.4%**	91.3%	74.3%
World	**97.7%**	**38.0%**	**109.5%**	**90.9%**	**149.2%**	**79.0%**	**95.8%**	**52.5%**	**83.2%**	**101.3%**	**73.0%**

Table S7. Withdrawal levels in 2004 and 2050 by SSP in km^3

Region	2004	2050		
		SSP1	SSP2	SSP5
South Asia	301.28	296.32	296.32	295.68
Northern Africa	166.12	190.72	186.39	198.28
Middle East	239.78	274.01	273.00	283.69
India	599.56	822.02	814.54	843.20
Central Asia	72.75	105.42	107.03	109.94
China	372.47	312.79	315.35	302.49
USA	158.39	184.57	182.37	189.17
Southern Europe	66.33	63.28	62.99	63.97
Southern Africa	11.36	10.68	10.63	10.90
North Latin Am	95.14	105.56	104.65	106.15
Southeast Asia	196.97	185.84	184.33	187.30
Australis&NZ	14.56	16.30	16.06	17.29
Northeast Asia	9.09	9.53	9.49	9.60
South Latin Am	20.28	24.40	24.14	25.15
Central Africa	16.02	27.55	24.77	30.44
Sahel	8.09	8.63	8.28	8.98
Eurasia	20.05	19.66	19.61	19.53
Brazil	10.70	10.32	10.26	10.42
Northern Europe	0.97	1.18	1.18	1.22

Figure S2. Global irrigation water requirements by SSP

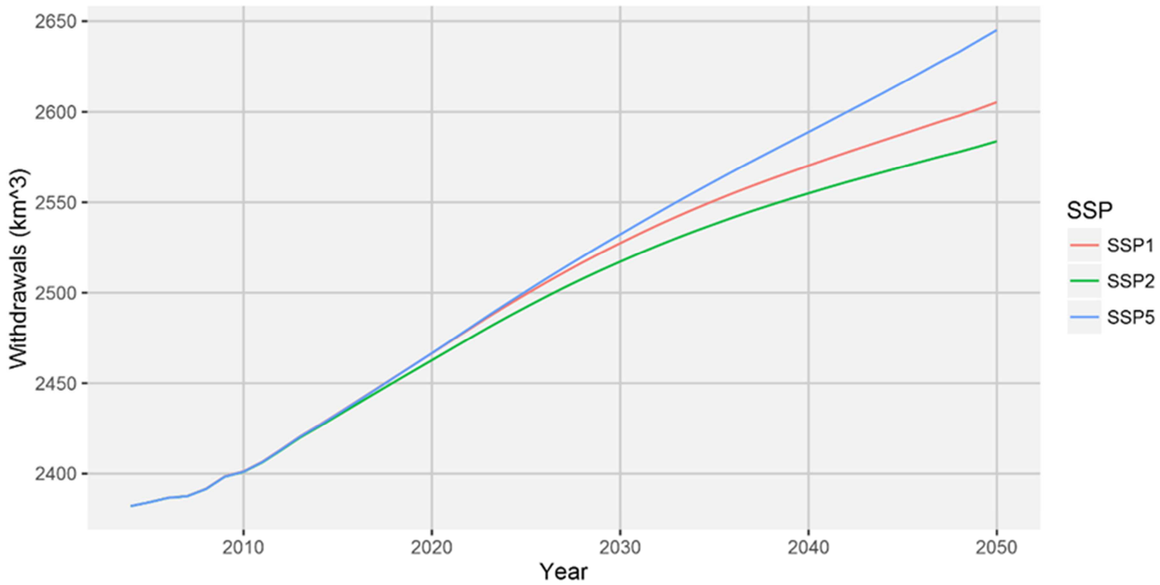
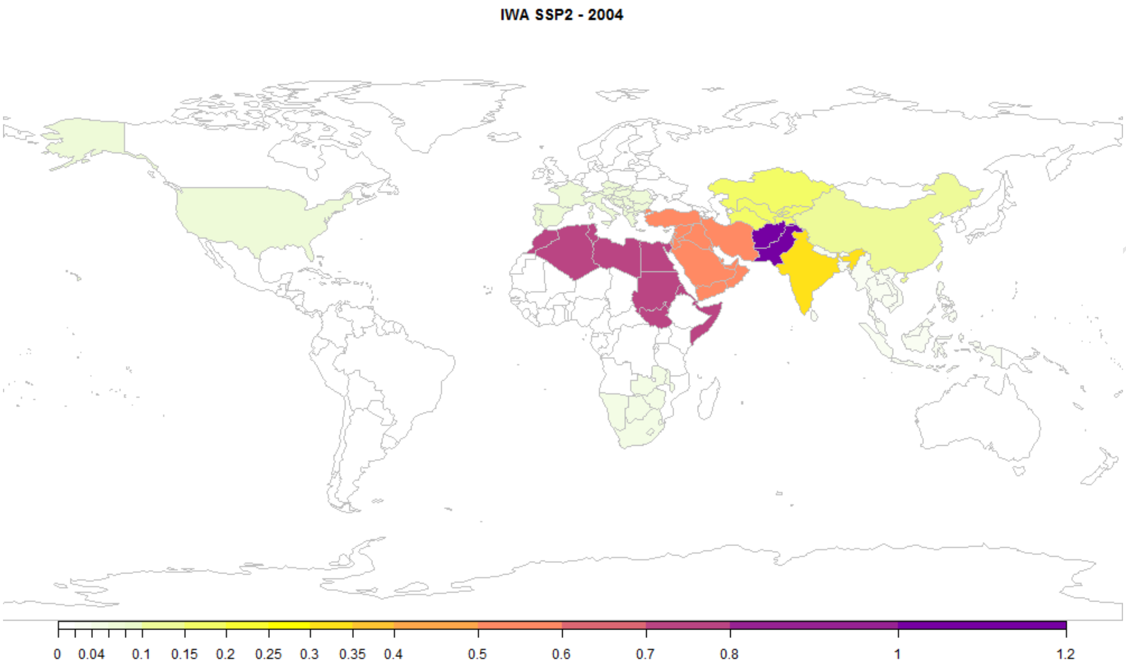
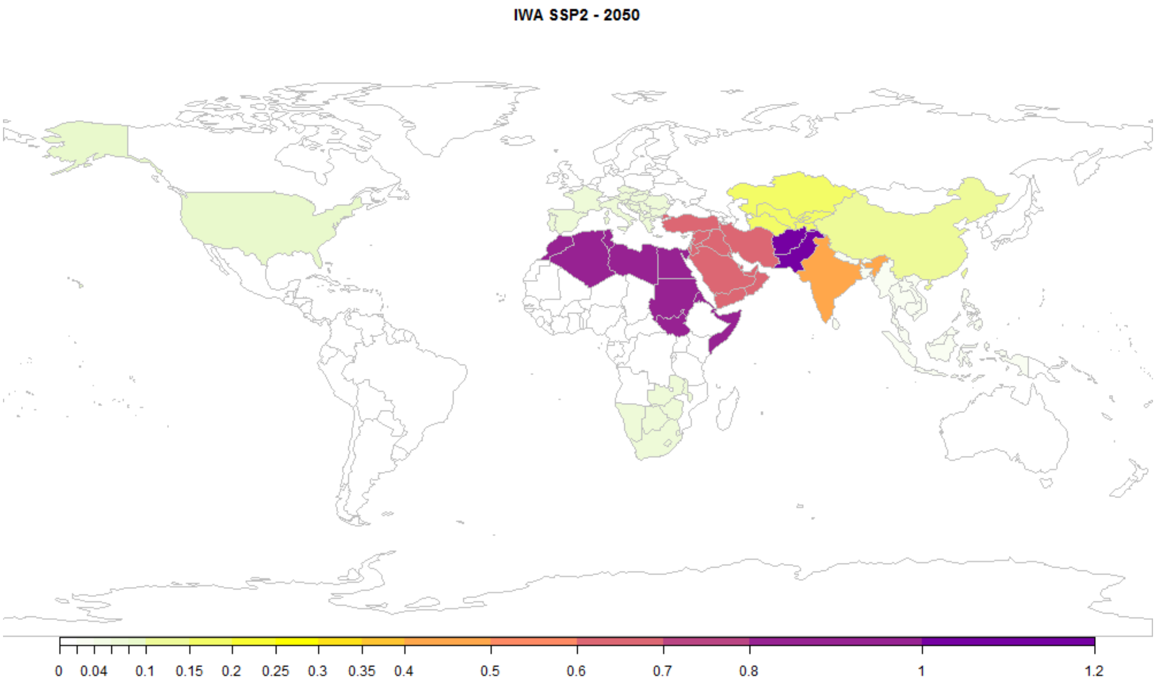


Figure S3. IWA heat maps – SSP2 2004 and 2050



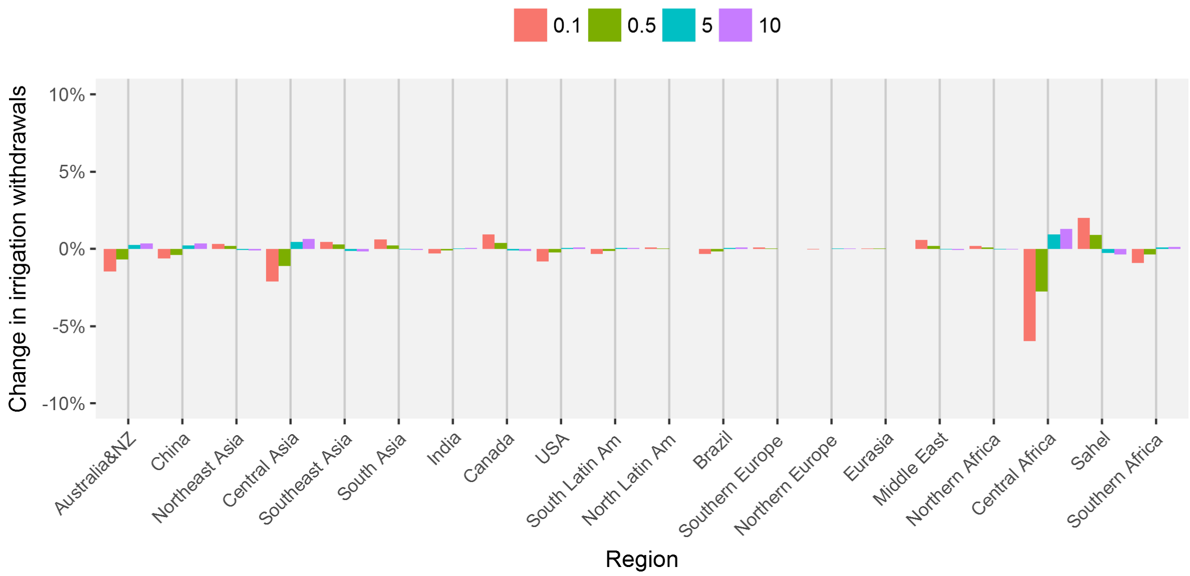


A3. Land conversion sensitivity analysis

To test the robustness of model results in relation to land conversion assumptions, we ran a sensitivity analysis by varying the CET elasticity $\boldsymbol{\sigma}_{AL}$. For most regions, a reduction in the elasticity leads to a reduction in withdrawals as a marker of increased friction in converting rainfed land to irrigated land, whereas an increase in the elasticity value leads to higher withdrawals.

Overall, irrigation withdrawal changes are small and do not influence the conclusions significantly regarding the pressure of irrigation withdrawals over the renewable resource base in each region (Figure S4). This is particularly important for high elasticity values ($\boldsymbol{\sigma}_{AL}$=10) where the largest increase is 1.3% (Central Africa), whilst water scarce regions have negligible changes.

Figure S4. Changes in regional irrigation withdrawals. The different cases are determined by the different σ_{AL} values considered around the central value of 2. Changes indicate deviations from the withdrawal levels obtained in the central case for SSP2.



Supplementary Material B

B1. RESCU irrigation water accounting framework

The production of crops in RESCU is split into rainfed and irrigated types using the production data from the GCWM model [44]. GCWM is a crop simulation model dedicated to calculating green and blue water consumption occurring through crop evapotranspiration. To undertake this calculation, it combines monthly gridded data (5 arc-min resolution) for growing areas of 26 crop classes with national and sub-national statistics covering irrigated and rainfed production and yields. GCWM then determines annual water consumption requirements based on cropping patterns, daily climate conditions and daily soil water balances by using the Penman-Monteith approach [56]. Blue and green water consumption are thus calculated at the level of 402 administrative units for the 1998-2002 period. In addition to the actual crop production data, the GCWM model calculates drops in yields and production on irrigated land for crops under a water deficit caused by a 'no irrigation' scenario. For the RESCU database, the mean values for yields and consequently for production across the 1998-2002 period are updated to the 2004 simulation base year by factoring in crop-specific annual yield improvements due to technological change.

We derive the value of irrigation in two steps. First, we split crop production into the rainfed and irrigated varieties. Thus, the GCWM crop classes are mapped onto the eight GTAP classes. In this respect, representative FAO commodity prices are factored in to convert GWCM production physical quantities to dollar values. We then calculate output shares $\alpha_{crop,m,r}$ for the two growing methods *m* (rainfed or irrigated) that are consequently used in the GTAP Splitcom tool [57] to split the output for each crop sector in each region r into the rainfed and irrigated varieties:

$$\boldsymbol{\alpha_{crop,m,r}} = \frac{\boldsymbol{vom_{crop,m,r}}}{\sum_m \boldsymbol{vom_{crop,m,r}}} \qquad \textit{(5)}$$

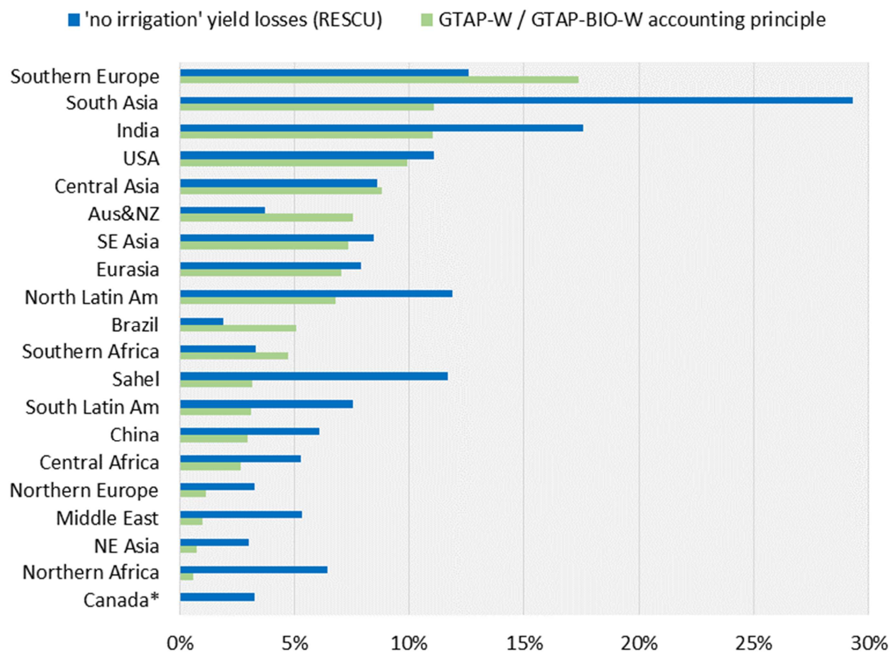
where $vom_{crop,m,r}$ represents the modified monetary value of GTAP crops derived from the GCWM production data. The production split is done by assuming an identical cost structure of the two varieties. The land rents that are part of the rainfed variety production costs become rainfed land rents, whilst land rents in the irrigated variety become rents to the *Irrigation-Land* bundle.

In the second step, the value of *Irrigation* is obtained as a share of the *Irrigation-Land* rents. The shares $\beta_{crop,r}$ are calculated as the ratio between the monetary value of lost production under the 'no irrigation' GCWM scenario and the initial value of irrigated output:

$$\boldsymbol{\beta_{crop,r}} = \frac{\boldsymbol{losses_{crop,irrigated,r}}}{\boldsymbol{vom_{crop,irrigated\ r}}} \qquad \textit{(6)}$$

The use of yield losses information for the GCWM 'no irrigation' scenario leads to significantly different outcomes for the value of irrigation compared to the accounting method used in GTAP-W and GTAP-BIO-W. In these models, it is assumed that when irrigation is disabled yields on irrigable land equal those on the rainfed type. This assumption is oversimplifying as from the GCWM 'no irrigation' data, we obtained that in only a fifth of cases yields on irrigable land without irrigation are similar to those on rainfed land (see Section B2 below).

Figure S5 - Regional value share of irrigation input in irrigated crop costs – comparison of the two accounting principles. The use of 'no irrigation' yields largely leads to a higher weight of irrigation in the crop production costs. *negative value added of irrigation obtained through the principle used in GTAP-W/GTAP-BIO-W.



Source: own compilation

Figure S5 compares the weights of irrigation in total irrigated crop costs for the two irrigation valuation principles. By using the 'no irrigation' production losses, the value of irrigation is increasing in most regions. Consequently, the share of irrigation in irrigated output for water-scarce regions (South Asia, India, Middle East and Northern Africa) grows considerably. At the same time, in some areas, the initial irrigated yield values are consistently inferior to those on rainfed land. Thus, applying the valuation principle from the other two GTAP-based models leads to a negative value added of irrigation, i.e. yields are improved when irrigation is not used. Therefore, in Canada, the comparison of results using the two valuation methods is not even possible.

B2. Comparison of irrigation valuation methods in GTAP-based models

In GTAP-W [21] the value of land entering crop production is split into rainfed land and an irrigable land-water composite (Figure S6) based on production share values obtained from the IMPACT model. Next, the value of the latter is further separated into irrigable land and irrigation water based on yield differences between irrigated and rainfed areas.

With GTAP-BIO-W [23], irrigated and rainfed land endowments are split by first specifying the production on each land type in a distinct function. At this stage in the disaggregation process, it is inferred that the cost structure of the two varieties is identical. The shares used to break the initial GTAP crop output is determined by irrigated and rainfed production values derived from *Portmann et al.* [58]. The value of rainfed land is equalised to the sum of land value added entering rainfed production of all GTAP crops, whereas total land value added in irrigated crop production equals the value of a land-water bundle. Land-water is then split into (irrigated) land and water based on differences between output values per hectare of irrigated and rainfed land within the same region (Figure S7).

Table S8. Irrigation water valuation steps in GTAP-based water models

Model	Rainfed/Irrigated production distinction	Irrigation water / irrigable land value distinction
GTAP-W	No – land is split in rainfed and irrigated instead	Based on yield differences from the IMPACT model
GTAP-BIO-W	Based on production shares from MIRCA2000 [*Portmann et al.*, 2010]	Based on yield differences from MIRCA2000 *[Portmann et al.,* 2010]
RESCU	Based on production shares from GCWM [*Siebert & Döll,* 2010]	Based on value of lost production – ‘no irrigation’ scenario of the GCWM model

Hence, both models use the same premise concerning the effect of irrigation on production: that in the absence of irrigation water, yields on irrigated land return to the values observed on rainfed land (Table S8). In the irrigation water accounting framework for the RESCU model, we challenge this assumption. In many instances, the practice of irrigation takes place on land that is endowed with different growing conditions compared to the rainfed variety within the same region. In this regard, we employ the ‘no irrigation’ scenario of the GCWM model which determines the production and yield outcomes for irrigated land when the irrigation facility is turned off. Figure S7-A confirms that yields on irrigated land using irrigation are superior to rainfed land in most cases. However, in the ‘no irrigation’ scenario, yields on irrigable land rarely return to values similar to those on rainfed land (Figure S8-B), with the large majority of cases leading to diverging outcomes (with both poorer and better yield results).

Figure S6. GTAP-W crop production tree. Source: Calzadilla et al. [21]

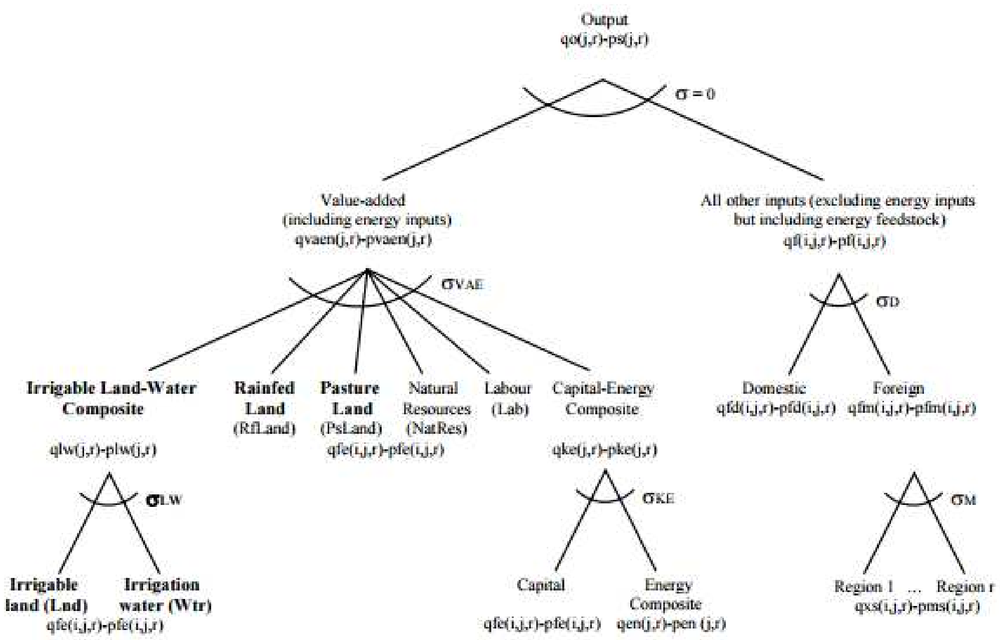


Figure S7. GTAP-BIO-W crop production tree. Source: Taheripour et al. [23]

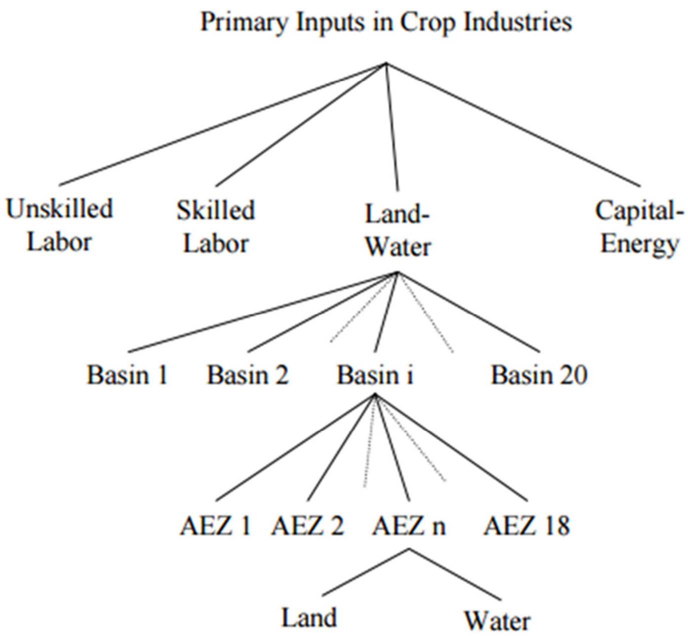


Figure S8. Yield comparison of irrigated and rainfed land across the 140 regions and 8 crop classes in GTAP v9. *yields differing by no more than ±5%. Actual yields on arable land with irrigation are largely superior to those on rainfed land (A). With no irrigation, yields on irrigable land are mostly different to those on rainfed land (B). Calculation: GCWM yields for the two scenarios (actual and 'no irrigation') mapped onto the GTAP crop classes. In 510 out of 1120 cases, either one or both growing methods were absent at the GTAP regional level.