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The impacts of higher CO_2 concentrations over global crop production and irrigation water requirements

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Abstract

Increases in CO_2 atmospheric concentrations are expected to lead to multiple and possibly opposing effects over crop performance. The paper uses a global economic model (RESCU-Water) to analyse the impacts of changes in climatic conditions and CO_2 fertilisation on crop output and on the pressure over water resources coming from irrigation. RESCU-Water is built on a Computable General Equilibrium Framework and distinguishes between the rainfed and irrigated production of eight crop classes. Irrigation is introduced as a separate production factor using a novel valuation method. The yield and irrigation water intensity effects employed to map climate change incidence are derived from spatially-detailed crop modelling using multiple climate datasets. The impacts are analysed for the 2004-2050 timeframe and are measured as deviations from a perfect-mitigation SSP2 baseline. Changes in climatic conditions decrease output and depress the demand for irrigation, whilst discrepancies between tropical and temperate regions increase with concentration levels. Embedding CO_2 fertilisation more than offsets these adverse effects by determining a net increase in crop production and a reduction in irrigation water requirements at a regional level. The resulting water savings potential even in the lower concentrations scenario (RCP2.6) warrant more research with the aim of reducing the uncertainty regarding the effects of CO_2 fertilisation.

Key words: Computable General Equilibrium, Global water requirements, Crop production, Irrigation, Climate change, CO_2 fertilisation, Water stress indicators

JEL Classification: D58, Q13, Q25, Q54, Q56

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1. Introduction

Anthropogenic climate change is expected to have a significant impact over agricultural output (Porter et al. 2014). The relationship between increases in concentrations of greenhouse gases, in particular CO_2, and crop growth is composed of multiple and possibly opposing effects (Gornall et al. 2010). On an annual basis, crop yields would be affected directly by changes in mean climatic conditions (temperature, precipitation, length of growing seasons) but also indirectly through the fertilisation effect of CO_2 due to enhanced photosynthesis of C3 plants.

From a water use perspective, CO_2 fertilisation (CF) may also lead to higher crop water efficiencies through a lower transpiration at the leaf level (Wullschleger et al. 2002). This could significantly alter water requirements for crop production and could thus have a noticeable impact over run-off (Betts et al. 2007) and implicitly on the water availability for non-agricultural uses. At the same time, changes in precipitation patterns would modify the natural soil water balance and would influence the intensity of blue water usage on irrigated land (Döll 2002; Fader et al. 2010; Gerten et al. 2011).

Irrigated land provides two fifths of world crops whilst 70% of global freshwater withdrawals are dedicated to irrigation. Growth in crop output induced by expected socio-economic development will further increase irrigation water requirements (Alexandratos & Bruinsma 2012). Therefore climate change becomes a further complicating factor regarding the pressure over freshwater resources that stems from the need to meet global food demand in the future.

Many global studies have been dedicated to determining the effects of changes in mean climatic conditions over crop output. However, most economic analyses have avoided embedding the effect of CF despite its potential non-negligible implications over irrigation water requirements and land use. A main deterrent for this is the uncertainty to whether CF will materialise. Whilst laboratory trials have so far been conductive to the enhancing effect of higher CO2 concentrations over yields, large scale experiments are still under development.

Despite the uncertainty of CF, global crop models have by now integrated this effect in relation to yields and crop water productivity (Deryng et al. 2016). Hence, in this paper we make use of the recent crop data to explore this additional dimension in the relationship between climate change, crop production and irrigation water requirements through an economy-wide modelling framework. We account for changes in yield and irrigation water intensity as determined by the LPJmL crop model for ISI-MIP (Warszawski et al. 2014) for the two fertilisation variants (with and without CF) across two RCPs (2.6 and 8.5). These key parameters are calculated using climate data from three global circulation models (GCMs). The alterations to crop performance are then applied to the RESCU-Water CGE model to measure deviations of global crop output and water requirements compared to a baseline calibrated onto the SSP2 “middle-of-the-road” pathway in the 2004-2050 timeframe.

Crop production in the RESCU-Water model distinguishes between rainfed and irrigated growing methods to capture the differentiated incidence of climate change and the substitution effect between the two varieties. Although the consequences of changes in crop output over food security are important, however, the emphasis in this paper is placed on the changes in water requirements for irrigation and the implications of these changes for future water scarcity.

2. Climate change and irrigation water in CGE models

Due to the multi-sector and multi-factor representation of the economy, CGE models can be employed to capture the different water use patterns through the different users e.g. crops, industry or households. Given that water demand is tied to demographic and economic growth, the opportunity of using CGE

models for water use assessments is also determined by the frameworks capacity to capture the allocation of factors of production such as capital and labour.

This modelling framework has been employed at a global scale to analyse the relationship between socio-economic development, crop output and climate change (Wiebe et al. 2015; Nelson et al. 2014). However, in terms of impacts over natural resources, most of the models involved focus on the land-use aspect of crop production.

An early attempt to add the water dimension in a CGE framework was made through the BLS model. Parry et al. (2004) use combined crop and CGE modelling to derive the effects of changes in crop yields and socio-economic drivers of SRES scenarios over crop prices and output. An advancement to this analysis is done in Fischer et al. (2005) and Fischer et al. (2007) where agro-ecological zoning is introduced to better reflect climate change incidence over crop growing conditions. Fischer et al. (2007) focuses on irrigation water requirements given crop water deficits induced by climate change. Irrigated production is treated exogenously as a share of total crop output with values derived from FAO projections. Therefore, the substitution effects between the rainfed and irrigated varieties of the same crop determined by yield differentials are not captured. In addition, irrigation water demand is not treated separately to capture the variations in water intensities of the different crop classes but follows the changes in overall crop land expansion.

Whilst the distinct modelling of water in CGE modelling has been done extensively at national or river-basin levels (Dixon et al. 2011; van Heerden et al. 2008; Luckmann et al. 2014; Strzepek et al. 2008; Hassan et al. 2008; Letsoalo et al. 2007), for global scale analyses this has materialised in only a few instances and only for crop production – GTAP-W (Calzadilla et al. 2011a), GTAP-BIO-W (Taheripour et al. 2013). The difficulty of representing freshwater as a distinct factor of production at a global level stems from the heterogeneity or even the absence of water valuation across world regions. Therefore, these global models have made important steps towards the shadow pricing of freshwater in crop production by taking into account production and yield data differentiated by the rainfed and irrigated growing methods.

Calzadilla et al. (2013) use GTAP-W to analyse the impacts of climate change over crop output and welfare in 2020 and 2050 for the SRES A1B and A2 scenarios. Crop yields are embedded as a function of precipitation, CO_2 fertilisation and temperature whilst irrigation and land supply depend on river flow and rainfed land soil moisture respectively. In Calzadilla et al. (2011b) the model is further used to measure the compounded effects of climate change and the Doha Round international trade tariffs.

A common specification in GTAP-W and GTAP-BIO-W is that the supply of irrigation water is treated exogenously. For GTAP-W, the supply follows changes in river flow as calculated by hydrological models and thus overlooks the stocks and flows related to groundwater resources. GTAP-BIO-W adjusts the irrigation water availability based on the Irrigation Water Reliability Index from the IMPACT model (Rosegrant et al. 2012) which uses the value total renewable water resources (TRWR) as reference point. Therefore, by deciding the water availability for agriculture outside the model framework, it is not possible to calculate any change in irrigation water requirements given climate-induced changes in yields and water intensities.

RESCU-Water treats the supply of water for irrigation as an endogenous variable which follows the market prices of factors of production. The underlying assumption is that an upper limit to freshwater withdrawals for crop production cannot be established as long as the other water user types are not considered in an integrated fashion. In addition, considering that over-exploitation is already occurring in some river basins (Döll et al. 2014; Long et al. 2015; Wada et al. 2010), withdrawals above the TRWR levels are also plausible both presently and in the future. The irrigation water requirements calculated in RESCU-Water provide thus a measure of the pressure exerted by irrigated crop production

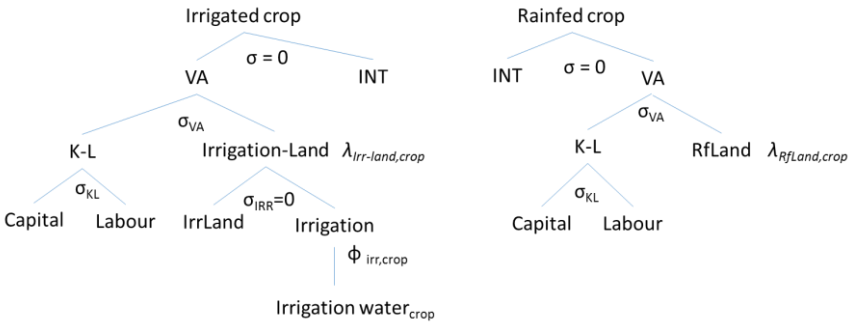
over freshwater resources. This pressure is linked to socio-economic development and to changes in crop growing conditions coming from higher CO_2 concentrations.

3. Methodology

3.1. RESCU-Water model

To capture the market interactions determined by changes in crop performance we use the RESCU-Water (Resources CGE UCL Water) model. The model is built on a global recursive-dynamic framework and relies on the GTAP v9 database. The eight GTAP crop classes are disaggregated to obtain a distinct representation of their rainfed and irrigated production functions (Figure 1). The advantage of separating crop output by growing method consists in the ability to differentiate the climate change incidence over the two varieties.

Figure 1 - RESCU irrigated and rainfed crop production functions. Irrigation water use is tied to the *Irrigation* factor through a crop-specific irrigation water intensity.



Water variables

Irrigation is introduced as a standalone factor using an improved accounting methodology relying on the 'no irrigation' scenario of the GCWM model (Siebert & Doll 2008). The initial value of irrigation is determined by the improvements brought to yields relative to the simulated levels when the irrigation facility is absent.

The model endogenises the regional supply of irrigation and thus has the ability to determine changes in irrigation water uses as a function of market prices. The supply function takes a logistic functional form which allows the expansion of irrigation given an upper limit $IrrMax_r$, changes to the price of irrigation $PIrr_r$ and the market price index $PINDEX_r$:

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

Physical blue water uses are tied to the use of the *Irrigation* factor through a water intensity parameter $\phi_{crop,r}$. The parameter is region- and crop-specific and is calibrated using the blue water consumption figures from GCWM. Regional irrigation requirements are calculated as a summation of uses in the production of the eight crop types:

$$Irrigation\ water\ requirements_r = \frac{\sum_{crop,r} \Phi_{crop,r} Irrigation_{crop,r}}{\eta_r} \quad (2)$$

where η_r is the regional irrigation efficiency to include conveyance and application losses of regional irrigation systems.

Water requirements are dependent on the total supply of irrigation but also on its allocation across the different crop classes given the equilibrium production mix. In this paper, changes in the crop production structure and crop output can be determined by changes in relative yields of crop varieties and crop classes. Hence, with irrigation being a mobile factor of production, water requirements can increase when irrigation is re-allocated from less to more water intensive crop classes and conversely.

Land variables

Considering that land and irrigation in irrigated crop production are specified as perfect complements, irrigated land availability and the rainfed-to-irrigated land conversion also act as constraints to irrigation use expansion. Rainfed (*RfLand*) and irrigated land (*IrrLand*) are supplied through a CET function which allocates arable land into the two land types. The supply of arable land is endogenous and is limited by the crop land suitability within each region.

Yield changes are specified through the $\lambda_{IrrLand,crop}$ and $\lambda_{RfLand,crop}$ efficiency parameters for irrigated and rainfed land inputs respectively. In addition to climate change impacts over land productivity, yield growth induced by technological advancements is also embedded in the baseline through the expected technological improvements as calculated by the IMPACT model (Nelson et al. 2010).

Socio-economic development

For this paper, the baseline socio-economic development is built around the "middle-of-the-road" SSP2 storyline (van Vuuren et al. 2014). Socio-economic change is reflected in the model through GDP and demographic evolution. Downscaled data is derived from the IIASA SSP database[2].

Target GDP growth is obtained through an economy-wide endogenous labour productivity. In addition, investment levels throughout the simulation period are adjusted to reflect the investment rates obtained by the macro-econometric MaGE model (Fouré et al. 2013).

The household utility function is introduced through a Linear Expenditure System (LES) specification. The functional form is calibrated for the base year using the GTAP income- and own-price elasticities. Hence, a subsistence consumption component is introduced and is updated annually to follow population growth. Changes in demographics also influence the labour supply through the evolution of the 16-65 age group within each region.

3.2. Data

Climate change impacts are embedded through two main channels –*yields* differentiated by crop class and by growing method (rainfed and irrigated), and *water intensities* of irrigated crops. Changes in these two parameter sets are determined using the LPJmL crop model output with data published on the ISI-MIP FastTrack platform[3]. The choice of LPJmL among all participating crop models in the intercomparison project was based on the largest coverage of scenarios in terms of crop classes, RCPs and CF variants.

The LPJmL yields and water data are calculated on an annual basis at an 0.5° spatial resolution and are based on changes in soil water balances and crop growing conditions (climatic and through CF). The crop model output is expressed in values per hectare and reflects the conditions in each raster point without taking into account actual crop production levels. Therefore, to aggregate these parameters at a regional level we employ the MIRCA2000 harvested area data (Portmann et al. 2010) mapped onto the LPJmL crop classes.

[2] https://tntcat.iiasa.ac.at/SspDb accessed 16 September 2016
[3] https://esg.pik-potsdam.de/search/isimip-ft/ accessed 15 October 2016

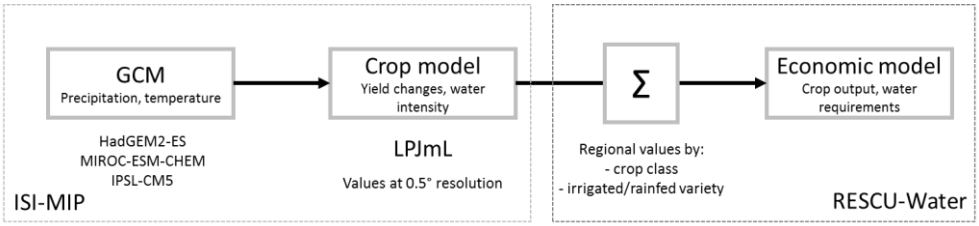
Yields per crop class *crop*, growing method *m* and region *r* are determined using the following weighted average:

$$Yield_{r,crop,m} = \frac{\sum_{p_r} area_{crop,p_r,m} * yield_{crop,p_r,m}}{\sum_{p_r} prod_{crop,p_r,m}}$$

p_r represent all the raster points within the region r. Harvested area for each crop LPJmL crop class $area_{crop,p_r}$ is taken from the MIRCA2000 dataset whilst yield data $yield_{crop,p_r}$ is determined by LPJmL (see the LPJmL–MIRCA2000 crop mapping in Table A1 in the Appendix).

Water intensities are calculated by tracking the changes of the LPJmL *potential irrigation water withdrawal* variable of each irrigated crop type and for each region. The regional aggregation is done in a similar fashion as for yields.

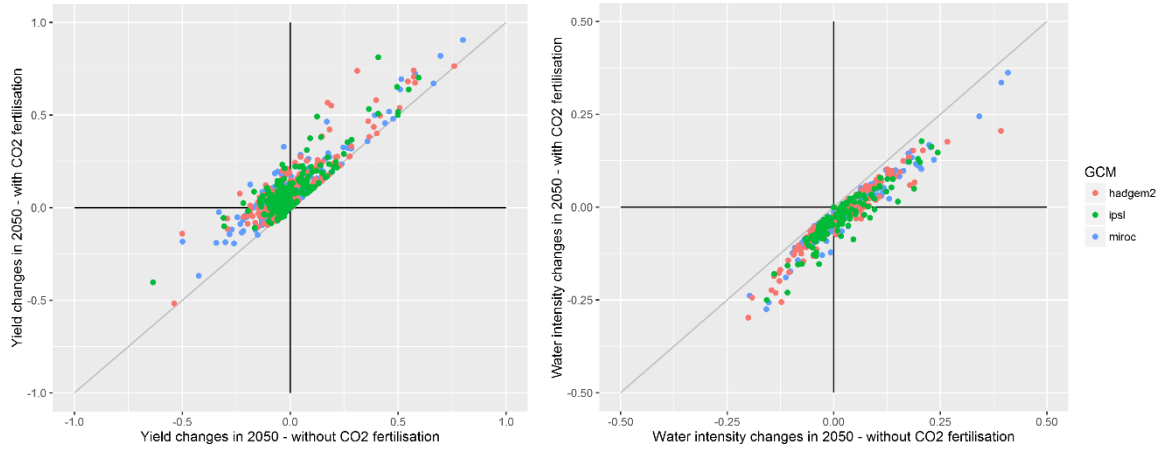
Figure 2 - Data treatment and integration



The data integration and treatment is illustrated in ***Figure 2***. In order to filter the effects of climate variability over model results, we use two-sided 21-year moving averages for both biophysical parameters. The simulation period for RESCU-Water being 2004-2050, the LPJmL data considered covers thus the 1994-2060 timeframe.

To address the uncertainty of climate change incidence, the crop model data is considered in relation to the climate data of three GCMs (MIROC-ESM-CHEM, HadGEM-ES, IPSL-CM5). Figure 3 shows the aggregated changes to yields and water intensities by GCM and allows for a comparison between crop performance with and without CF.

Figure 3 – LPJmL-aggregated RCP 2.6 yield and blue water intensity changes– with and without CF. Each point represents one crop variety (by crop class and growing method) within one RESCU region. Water intensities are applicable only to irrigated varieties. Yields see an improvement when CF is factored in (points above the diagonal) and most are even superior to those in the baseline (points above the X-axis). The opposite is applicable to water intensities suggesting a higher blue water productivity with CF.

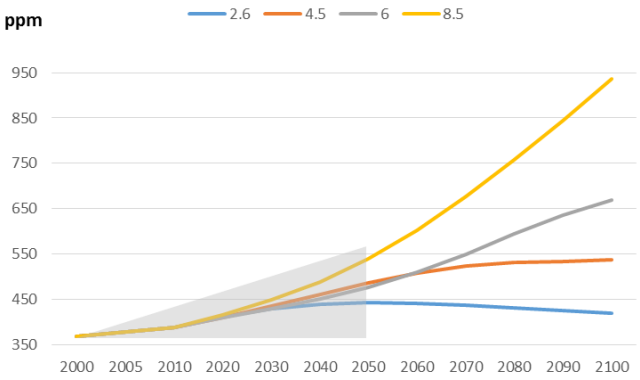


3.3. Scenarios

We seek to compare the model results between the lowest- (RCP2.6) and highest- (RCP8.5) radiative forcing scenarios. CO_2 concentrations between the full range of RCPs start to significantly diverge from 2025, and lead to a 100ppm span by 2050 (***Figure 4***). Therefore, as we move closer to the end of the simulation period, in addition to changes in climatic conditions, the size of the CF effect becomes increasingly sensitive to the concentration pathway choice.

Emission patterns for the SSP2 socio-economic scenario are projected in van Vuuren et al. (2014) to determine radioactive forcing levels in the RCP6.0-RCP8.5 range. However, we take the lower RCP2.6 into account in order to explore the implications of climate action over agriculture and irrigation water requirements.

Figure 4 - CO_2 concentrations 2000-2100 by RCP. Concentrations are determined by the IMAGE, MiniCAM, AIM, MESSAGE models for RCP 2.6, 4.5, 6.0 and 8.5 respectively



Source: RCP database http://www.iiasa.ac.at/web-apps/tnt/RcpDb, last accessed 17 October 2016.

Yield and water intensity changes are considered for both CF variants (with and without CF) in each RCP scenario (***Table 1***). Yield changes are implemented by modifying the baseline land efficiency parameters λ in the production function of each crop class and variety. Water intensity changes are reflected in the ϕ parameters attached to the irrigated crop types.

It should be noted that only yields act as shock variables in the RESCU-Water simulations - these determine a new economy-wide equilibrium through a change in the cost structure of crop production. The corresponding change in land and irrigation demand lead to an overall crop cost and market price effect but also to a substitution of these factors in relation to the other inputs to crop production. In contrast, the water intensities indicate the levels of water required by the *Irrigation* factor and are applied outside the model. Hence, these do not affect the supply and allocation of irrigation or land across crop classes.

Table 1 - Simulation scenarios

Main scenario	RCP	SSP	CF variant	GCM
1. Baseline	Perfect mitigation	SSP2	n/a	None
2.1 RCP 2.6 w/o CF	RCP 2.6	SSP2 calibration	No CO_2 fertilisation	HADGEM2 IPSL MIROC
2.2 RCP 2.6 CF			With CO_2 fertilisation	
3.1 RCP 8.5 w/o CF	RCP 8.5		No CO_2 fertilisation	
3.2 RCP 8.5 CF			With CO_2 fertilisation	

The RESCU-Water model was run separately for changes in the biophysical parameters corresponding to climate data of each of the three GCMs considered. The results for the main scenarios are reported however as averages across the three circulation models.

4. Results

4.1. Global impacts

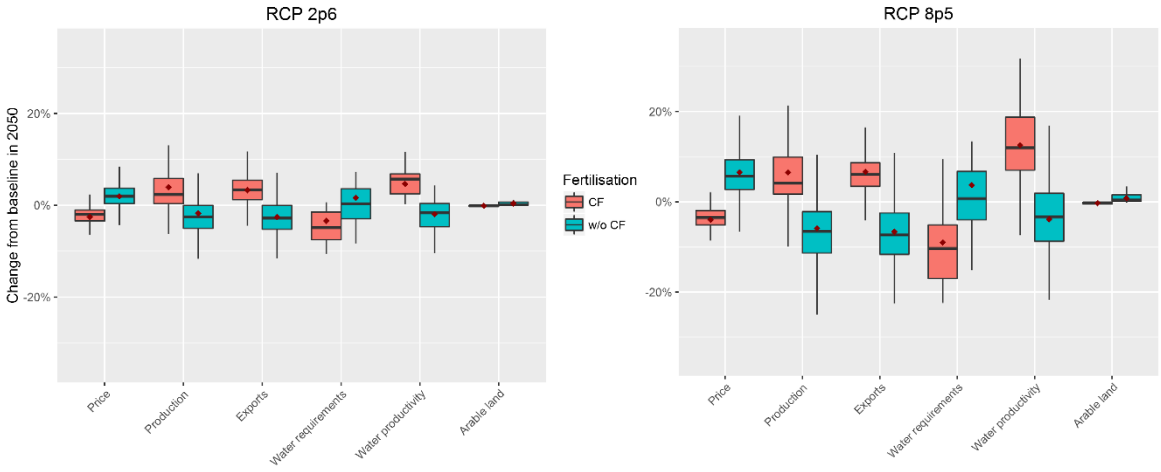
By 2050, changes in growing conditions have a visible impact over crop sectors even for the low emissions pathway RCP2.6. Deviations from the baseline and the variance of climate change incidence across regions increase with CO_2 concentrations. ***Figure 5*** illustrates the changes relative to the baseline equilibrium in 2050 to the main market variables related to crops (price, output and exports) and resource use (water requirements and arable land).

The size of crop international trade measured through regional exports changes in the same direction as crop output. Nevertheless, the variance between regions is lower when CF is embedded indicating that the addition of fertilisation narrows down the distributional effects determined by the alterations in climatic conditions.

The water productivity changes represented are endogenous to the economic model. These reflect the evolution of water intensities as calculated by the LPJmL model, but also include the alterations to the allocation of the *Irrigation* factor given the input substitution effect and changes in the crop production mix.

The cost effect of the yield evolution is noticeable through changes in crop market prices. The results show opposing impacts of the two CF variants. Whilst climate change increases prices and determines a reduction in crop output when CF is not considered, fertilisation more than offsets the loss of yields induced by climatic conditions, leading to overall crop price decrease and a boost to crop production compared to the baseline.

Figure 5 - RCP 2.6 and RCP 8.5 changes in main crop variables (% change from 2050 baseline values). The boxplots illustrate the combined results across crop types and regions. The whiskers and boxes indicate the 5th,25th ,50th, 75th and 95th percentiles. The diamonds represent the mean values.



Global water requirements decline with the increase in CO_2 concentrations in both CF variants. Without the CF effect, requirements are 1.1% and 5% lower than the baseline values for RCP2.6 and RCP8.5 respectively. This decline is primarily due to the overall decrease in crop production. However, part of this effect is counter-balanced by a reduction in irrigation water productivity.

Despite the expansion in crop output, CF determines an even higher reduction in water requirements - 4.1% (RCP2.6) and 12.2% (RCP8.5). Water productivity with CF increases significantly in most areas including dry and irrigation-intensive regions such as India, Middle East and Northern Africa, and thus offsets a growth in irrigation demand coming from the expanded crop production.

Changes in pressure are measured through the Irrigation Withdrawals to Availability (IWA) indicator[4] and are presented in ***Table 2***. China is the only region to face an increase in water pressure across all scenarios, whilst some other regions are adversely affected only when CF is not considered (e.g. Central Asia, Southern Europe, Southern Africa, Australia&NZ).

Table 2 - Irrigation Water to Availability changes

RESCU-Water Regions	Baseline 2050 No CC	no CO_2 fertilisation		CO_2 fertilisation	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
South Asia	102.78%	97.04%	90.85%	94.95%	85.76%
Northern Africa	88.43%	85.53%	83.21%	81.93%	75.27%
Middle East	62.38%	61.23%	60.51%	58.69%	54.08%
India	41.68%	39.24%	35.37%	38.58%	34.07%
Central Asia	19.75%	19.84%	20.90%	19.08%	18.84%
China	10.45%	11.94%	11.61%	11.60%	10.74%
USA	8.20%	7.97%	7.99%	7.69%	7.27%
Southern Europe	7.15%	7.67%	7.82%	7.20%	6.69%
Southern Africa	6.06%	6.08%	6.20%	5.93%	5.73%
SE Asia	2.84%	2.83%	2.84%	2.73%	2.58%
Australia&NZ	1.89%	1.93%	1.94%	1.90%	1.84%
NE Asia	1.84%	2.17%	2.44%	2.04%	2.11%
North Latin Am	1.42%	1.40%	1.39%	1.39%	1.33%
South Latin Am	1.23%	1.26%	1.26%	1.21%	1.13%
Sahel	1.00%	1.01%	1.01%	0.92%	0.82%
Central Africa	0.92%	0.97%	1.04%	0.84%	0.71%
Eurasia	0.42%	0.40%	0.40%	0.37%	0.34%
Brazil	0.14%	0.14%	0.13%	0.13%	0.11%
Northern Europe	0.07%	0.08%	0.11%	0.07%	0.08%
Canada	0.07%	0.06%	0.06%	0.06%	0.06%

4.2. Crop-specific impacts

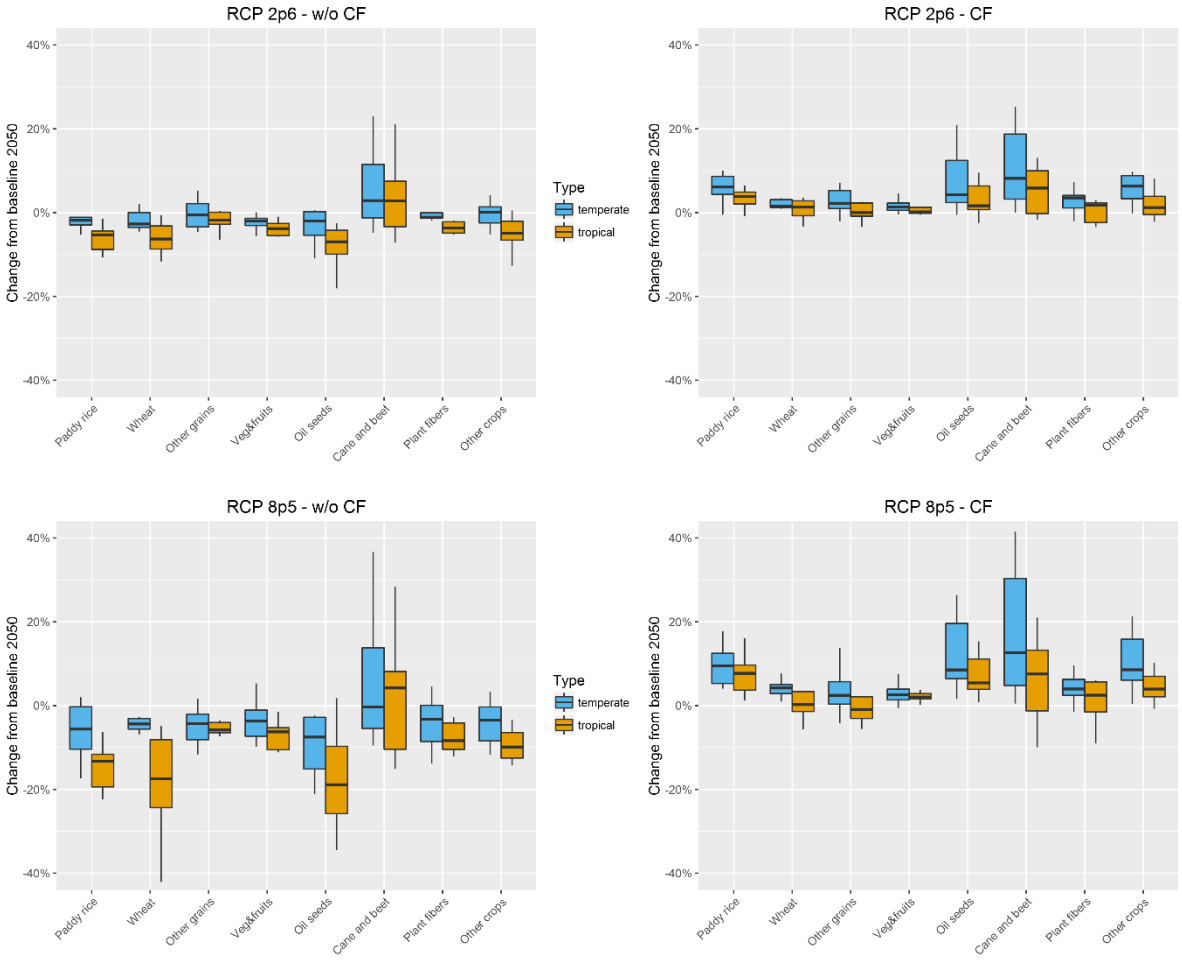
Several differences emerge between crop types in both CF variants. When CF is not factored in, regional crop output generally decreases. The highest negative impact occurs for paddy rice, wheat and oil seeds, whilst other grains (maize and tropical grains) are less affected. With CF embedded, the impacts are reversed as output compared to the baseline expands in most cases. For food crops, rice and oil seeds face the highest production growth, whereas wheat, other grains and vegetables&fruits are less sensitive.

[4] Calculated as the ratio between irrigation water requirements to total renewable water resources within each region.

The incidence of climate change can also be differentiated by grouping regions into their preponderant climate type (***Figure 6***). Without CF, changes in climatic conditions alone have a stronger adverse impact over crop output in tropical regions. The cane&beet group is mostly positively affected by changes in climatic conditions. As a C4 crop, sugar cane is indifferent to CF, hence the fertilisation effect for cane&beet is more visible in temperate regions where sugar beets[5] are grown predominantly.

Although the total effect over output relative to the baseline remains stronger in temperate regions, CF plays an important role in correcting some of the distributional effects of climate change over crops supply. When CF is embedded, except for the *other grains* group, tropical regions have a higher incremental change in output across all crop classes (see Figure A1 in Appendix).

Figure 6 - Crop output changes by RCP and CF variant



4.3. Decomposition of regional water productivity changes

Regional crop water productivity (CWP) is calculated as the ratio between total irrigated crop outputs to regional irrigation water requirements. Changes in CWP can be explained through the three main drivers: (1) water re-allocation across crop types through differentiated yield changes (endogenous), (2) changes in natural soil moisture of irrigated land (exogenous) and (3) fertilisation water efficiency gains from evapotranspiration (exogenous). The endogenous/exogenous distinction is made based on whether

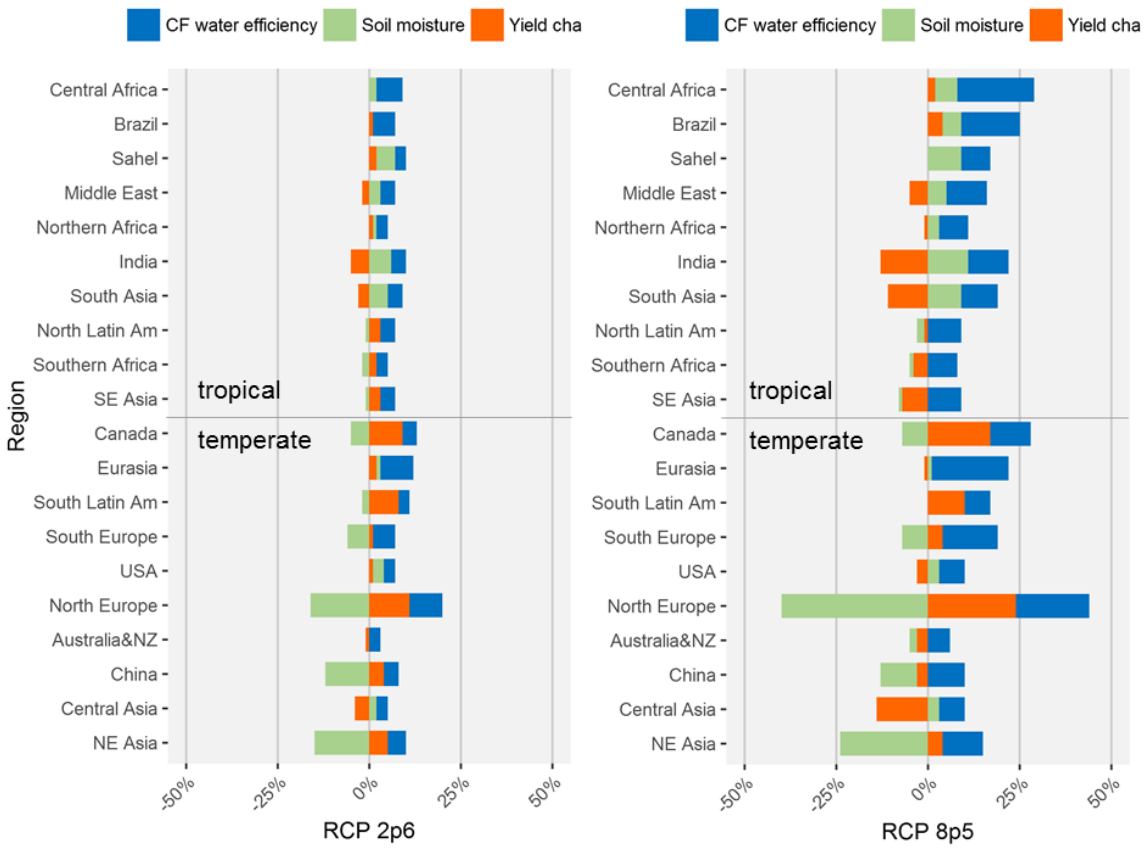
[5] Sugar cane and sugar beets are bundled in the GTAP database, hence they are represented together in the model

the driver determines or not a change to the RESCU model solution and implicitly on whether this affects crop output and irrigation allocation.

The effects are calculated as follows:

- *Yield changes* – changes in water requirements relative to the baseline with climate change impacts on yields but without changing the baseline water intensities
- *Soil moisture* – additional changes in water requirements by updating the water intensities to the "w/o CF" scenarios values. These reflect the changes in natural soil water balances when factoring in changes in climatic conditions
- *CF water efficiency* – additional changes in water requirements by further updating water intensities to "CF" scenarios values.

Figure 7 - Decomposition of water productivity changes in CF scenarios (2.2 and 3.2)



With CF embedded, CWP is higher than the baseline in all tropical regions, whereas the outcome is mixed for temperate areas as China and NE Asia continue to be negatively affected in both RCPs and Central Asia in RCP8.5. CF water efficiency increases CWP in all regions (***Figure 7***) and has the strongest impact among the three drivers in most cases. Hence this effect determines many regions to switch from a decline in water productivity to an increase, among which India and USA - regions which account for an important share in world irrigation withdrawals.

A contrast appears between tropical and temperate regions in which the impact of soil moisture over CWP is significant. Tropical areas generally benefit from higher soil moisture, hence they require less irrigation water to compensate for soil water deficiencies. Nevertheless, this positive impact is entirely or partially offset in water-stressed regions (India, South Asia, Middle East, Northern Africa) through irrigation re-allocations to more water-intensive crops.

An important observation is that the effects of water efficiency and soil moisture are amplified with the increase in CO_2 concentrations. This is also generally applicable for yield changes, with the exception of China, Eurasia, Southern Africa, USA and North Latin America where the sign of yield impacts shifts when moving from RCP2.6 to RCP8.5.

5. Conclusions

Higher CO_2 atmospheric concentrations lead to very different impacts depending on whether CF is taken into account. The contrasts between the two CF variants and the variance between regions increases with CO_2 concentrations.

Changes in climatic conditions lead to an overall decrease in output and in irrigation water productivity. The negative impacts are more pronounced for tropical than for temperate regions. Therefore, considering that the areas most affected are also those where most world population and economic growth will occur in the next decades, the adverse effects obtained raise food security concerns in line with other climate change impact assessments. Furthermore, the crop production mix could be altered towards more sugar output in the detriment of rice, wheat and oil seeds.

Without the CF effects over yield and water efficiency, water requirements are reduced due to the overall reduction in irrigated crop production. This is partially offset by a reduction in water productivity in some regions as production is shifted towards crops that are more water-intensive given relative yield changes. However, in other cases, mostly tropical regions, the natural soil moisture on irrigated land is improved.

A contrasting outcome is obtained when CF is embedded. Regional output generally increases across all crop classes, leading to a more balanced regional production of cereals, oils and sugars, whilst some of the regional disparities are also attenuated. Water requirements are considerably lower than the baseline given the overall boost in water productivity induced by CF water efficiency gains. This reduction in water demand of crop production could free up important water resources for other uses throughout the economy.

Considering the significant impact of CF over crop output and water resources, more work is welcome in order to reduce the uncertainty of this dimension of crop growth conditions. At the same time, a comparison of biophysical changes obtained by multiple crop models would be desirable for a diversity in modelling of yield responses and crop water efficiencies.

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Appendix

Table A1 - LPJmL - MIRCA2000 crop mapping

LPJmL crop	MIRCA crop class	MIRCA description
Wheat	1	Wheat
Maize	2	Maize
Rice	3	Rice
Millet	6	Millet
Soy	8	Soybeans
Cassava	11	Cassava
Sugarcane	12	Sugar cane
Sugar Beet	13	Sugar beet
Rapeseed	15	Rapeseed
Managed Grass	25	Managed grassland
Field Pea	26	Others (annual)

Table A2 – GTAP – LPJmL crop mapping for yield calculation

Application	**GTAP crop class**	**LPJmL crop**
Wheat	wht	Wheat
Paddy rice	pdr	Rice
Other grains tropical	gro	Millet
Other grains temperate	gro	Maize
Veg&fruits tropical	v_f	Cassava
Veg&fruits temperate	v_f	Field Pea
Cane and beet temperate	c_b	Sugar Beet
Cane and beet tropical	c_b	Sugarcane
Oil seeds	osd	Soy
Plant fibers	pfb	Managed Grass
Other crops	ocr	*Weighted average of the above*
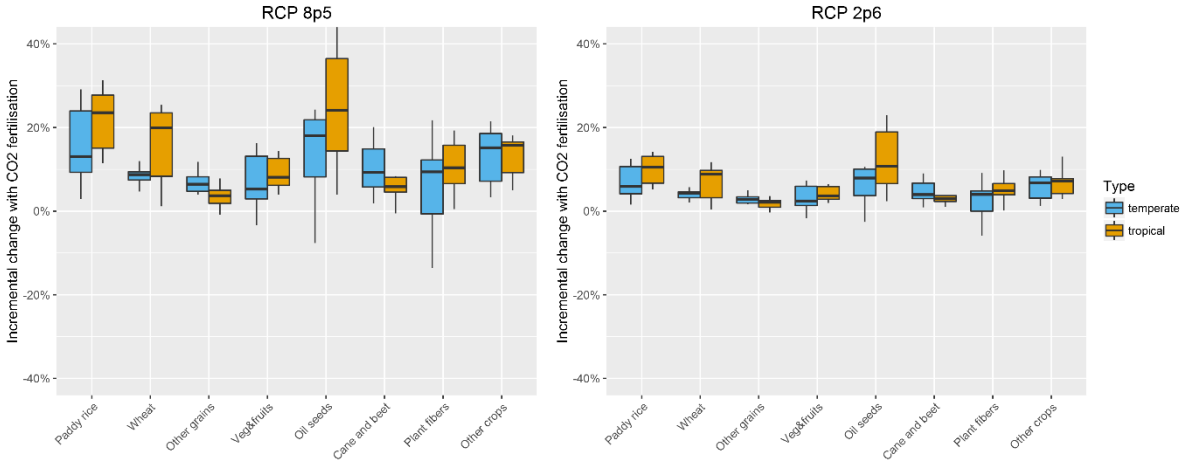
Figure A1 – Incremental output changes of CF. The changes are calculated as the difference between output between the two CF variants in each RCP