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Worldwide water constraints on attainable irrigated production for major crops

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Abstract

In order to achieve worldwide food security, there is a focus on sustainable intensification of crop production. This requires sustainable irrigation water use for irrigated croplands, as irrigation withdrawals are already resulting in groundwater exploitation and unmet ecosystem water requirements. Our study aims to quantify attainable wheat, maize, rice and soybean production on currently irrigated cropland under sustainable water use. Attainable production accounts for increases in nutrient application, while limiting irrigation withdrawals to renewable water availability and without compromising river ecosystem water requirements. Attainable production was quantified using a newly developed two-way coupled hydrological model and crop model. This model framework could comprehensively simulate biophysical processes related to water availability and crop growth under water and nutrient limitations. Our results indicate worldwide crop nitrogen uptake should increase by 20%, to achieve production gap closure. However, worldwide irrigation withdrawals should decrease by more than a third in order to ensure sustainable water use. Under these constraints, a total (all crops) production decrease of 5% was estimated, compared to currently achievable production. Moreover, achievable irrigated crop production in the extensively irrigated croplands of northeastern China, Pakistan and northwestern India would be reduced by up to a third. On the other hand, increases in achievable irrigated crop production may be possible in regions such as southern America, eastern Europe and central Africa. However, in these regions currently only a small fraction of crops is irrigated. Our results imply that intensification on currently irrigated croplands is at odds with sustainable water management, and further locally-oriented research is needed to assess suitable water management options and solutions.

1. Introduction

In order to achieve worldwide food security (sustainable development goal 2; [1]), sufficient food should be available all year round. Up to double of the 2005 worldwide crop production is needed to satisfy the food demands of a growing and more prosperous population by 2050 [2–4]. To achieve these goals, many studies have focused on (sustainably) intensifying agriculture in order to increase crop production [5–7]. In general, intensification is favored over expansion since intensification reduces competition for land with other anthropocentric activities, ecosystems and conservation [8]. Several studies have indicated that there is still a large gap between actual and potential crop production (the production gap). This gap could be closed through improved water and nutrient management [9–11].

Production gaps can be divided into several stages [12, 13]: potential production (no stress), water limited production (limited by water stress) and actual production (limited by water, nutrient, and biotic stress). Rainfed crops can attain water-limited production through increased nutrient application, while

irrigated crops are assumed to be able to attain potential production due to increased water availability. However, it is important to consider sustainable water use when addressing attainable irrigated crop production. The present day agriculture sector is the largest water user worldwide [14], and is reaching the planetary limits of sustainable water use [15, 16]. In many regions unsustainable irrigation withdrawals already result in groundwater-exploitation [17–19] and unmet ecosystem water requirements [20–22]. Moreover, competition with other water users is increasing due to socioeconomic developments and climate change [23].

Previous studies have addressed these water management issues from either a water availability perspective [24–26] or a crop production perspective [9, 12, 27]. However, only a few studies have addressed the impacts of sustainable water management on worldwide irrigated crop production. Jägermeyr *et al* [28] estimated the attainable irrigated crop production under sustainable water management using an dynamic vegetation model (LPJmL). However, in their study changes in nutrient application that would occur under production gap closure were unaccounted for. Rosa *et al* [29] estimated sustainable and unsustainable irrigation consumption under production gap closure, by combining simulations of potential crop water requirement and accumulated water runoff. Based on worldwide yield data [9] they estimated the potential production resulting from sustainable and unsustainable irrigation. However, their study did not estimate attainable crop production under water constraints as they did not model crop growth. Therefore, a knowledge gap remains in quantifying the combined effect of increased nutrient application (up to production gap closure requirements) and water constraints (under sustainable water management) on attainable irrigated crop production.

Our study aims to quantify worldwide attainable irrigated production for wheat, rice, maize and soybean. These four crops together cover 44% and 68% of worldwide rainfed and irrigated cropland respectively [30], and account for around 60% of worldwide calorie production [2]. Our study will answer the following question: Where is irrigated crop production constrained by sustainable water use, and what is the attainable production under these constraints while accounting for increases in nutrient application? To quantify attainable irrigated crop production, the variable infiltration capacity hydrological model (VIC; [31–33]), was integrated with the world food studies crop model (WOFOST; [34, 35]). This two-way coupled framework, called VIC-WOFOST henceforth, is able to comprehensively simulate biophysical processes related to water availability and crop growth under water and nutrient limitations. Further details regarding the VIC and WOFOST model integration is given in section 2.1,

while simulation details are found in section 2.2. In sections 3.1 to 3.3 the results of our research are presented. These results are followed by a discussion and the main conclusions in sections 4 and 5 respectively. Note that a model performance and sensitivity analysis is included in appendices A and B respectively.

2. Methods

2.1. The VIC-WOFOST model framework

This study was performed using the newly-developed VIC-WOFOST model framework. VIC is a macro-scale hydrological model that simulates the sub-daily water and energy balance (e.g. interception, evapotranspiration, percolation, and surface and sub-surface runoff; [31, 32]) and anthropogenic water-use (i.e. domestic, industrial, energy, livestock and irrigation withdrawal and consumption; [33]). VIC has been used extensively in studies ranging from global streamflow simulations and hydrological climate sensitivity [36–38] to anthropogenic impacts of irrigation and dam operation on water resources [33, 39–42]. WOFOST is a field-scale crop model that simulates daily crop growth (e.g. phenological development and biomass assimilation and partitioning; [35, 43]) and the effect of nutrient limitations [44]. WOFOST has been used extensively in studies ranging from monitoring and predicting yields [45–49] to estimating the effects of climate change and management strategies on crop growth [50–53]. The VIC-WOFOST model framework integrated the hydrological model and crop model using a two-way coupling (figure 1). Hydrological simulations were computed on a 0.5° grid, each containing various land-cover classes [30, 54]. For each wheat, maize, rice and soybean land-cover class, crop growth was simulated using the crop model. Crop water availability (soil and evapotranspiration components) is directly derived from the hydrological simulation, while hydrological land-cover characteristics (leaf area index, drought resistance, rooting depth and crop height) are directly derived from the crop simulation.

Simulated crop production was, among other factors, affected by soil moisture availability (i.e. crop water stress) and nutrient availability (i.e. crop nutrient stress). In case of crop stress, several crop growth processes are affected in the model: (a) biomass assimilation (i.e. growth) decreases, (b) leaf growth reduces, (c) biomass partitioning changes to favour root growth, and (d) senescence (i.e. aging processes) of various plant organs increases. Where soil water availability was simulated by the hydrological model, soil nutrient availability was based on (organic and mineral) fertilization application [9, 55, 56] and mineralization rates [57], which were given as input. In our study only nitrogen availability was accounted for, as our model could not account for phosphorus and potassium legacy effects.
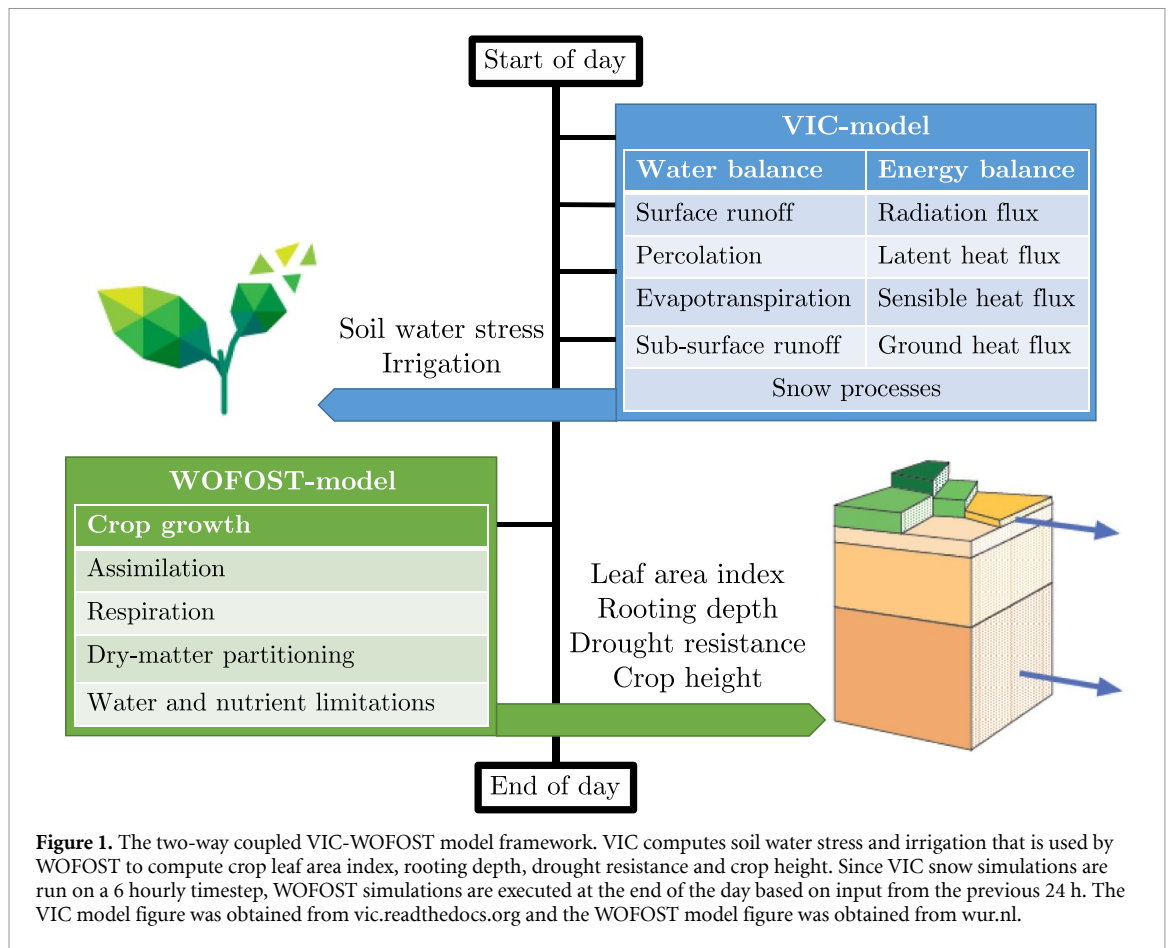
Figure 1. The two-way coupled VIC-WOFOST model framework. VIC computes soil water stress and irrigation that is used by WOFOST to compute crop leaf area index, rooting depth, drought resistance and crop height. Since VIC snow simulations are run on a 6 hourly timestep, WOFOST simulations are executed at the end of the day based on input from the previous 24 h. The VIC model figure was obtained from vic.readthedocs.org and the WOFOST model figure was obtained from wur.nl.

Anthropogenic water use (as discussed below) was simulated following Droppers *et al* [33]. Surface and subsurface runoff was routed using a routing scheme [58] and a reservoir operation scheme [59]. Under sustainable water management, part of the river streamflow was allocated to satisfy the water requirements for river ecosystems (environmental flow requirements), following the variable monthly flow method (60%, 45% and 30% of streamflow during the dry, intermediate and wet season respectively; [20]). Remaining river streamflow was available for anthropogenic use in the domestic, industrial, energy, livestock and irrigation sector (in that order). Note that all other sectors were prioritized over irrigation, meaning irrigation would be constrained first. Irrigation demands were calculated based on the soil moisture content (see also supplementary figures S.2 and S.3 (available online at stacks.iop.org/ERL/16/055016/mmedia)). During periods of water stress, irrigation demands were set to fill soil moisture up to saturation (for paddy rice) or field capacity (for other crops). When anthropogenic water demands exceeded available river streamflow and local dam reservoir storage, water demands could be withdrawn from non-renewable water resources (e.g. groundwater aquifers). The exception was energy water demands, which were exclusively withdrawn from river streamflow. Non-renewable water withdrawal contributed to a water deficit, which subsequently

reduced subsurface runoff until the deficit was fulfilled. Non-consumed anthropogenic water withdrawals were returned to the river streamflow. Further model information is given in supplementary information S.1.

2.2. Simulations and setup

In order to investigate attainable irrigated production, four simulations were run: (a) a *potential simulation*, (b) a *baseline simulation*, (c) a *restricted simulation*, and (d) a *attainable simulation* (table 1). The *potential simulation* estimated the upper crop production under current climate conditions. As such, crop growth was unlimited by nutrient and water availability. The *baseline simulation* was used to simulate crop production under contemporary nutrient limitations and water limitations for rainfed croplands. For both potential and baseline simulations, irrigation withdrawals were unrestricted, such that water is first withdrawn from renewable streamflow resources and subsequently from non-renewable water resources. Crop production gaps, resulting from water limitations (for rainfed crops) and nutrient limitations (for rainfed and irrigated crops), were estimated based on the difference between potential and baseline production. The *attainable* and *restricted simulations* are used to explored crop production when limiting irrigation withdrawals to renewable water availability (i.e. river streamflow and groundwater recharge)

Table 1. Model simulation setup used in our study. Nutrient limitations were based on contemporary fertilizer and mineralization rates. Non-renewable water withdrawals enable (unlimited) irrigation when renewable water resources were insufficient. Environmental requirements constrain irrigation withdrawals to guarantee water availability for river ecosystems.

Simulation	Nutrient limitations	Non-renewable withdrawals	Environmental requirements
Potential		x	
Baseline	x	x	
Restricted	x		x
Attainable			x

and guaranteeing environmental flows. The *restricted simulation* accounted for contemporary nutrient limitations, while the *attainable simulation* explored irrigated crop production under increased nutrient application, where nutrients are no longer limiting crop growth. Attainable and restricted simulations were compared to indicate the extent that nutrient application increases may help offset the effects of water constraints under sustainable water management.

Sub-optimal production, related to for example fertilizer use efficiency, seed selection, farming technologies, labor, biotic stressors (e.g. pests, weeds), and other management aspects [60] are not accounted for (i.e. no calibration has taken place). While these elements play a role in determining actual crop production [61], they do not limit attainable crop production. As such, our simulations represent the upper production limit under the given water and nutrient availability, which is an optimistic assessment.

Simulations were run between 1981 and 2016 with a daily timestep (and a 6 hourly snow timestep). However, results were analyzed for the years 1990 to 2010, as this period covers the land-use reference period [30]. Weather variables (air temperature, radiation, precipitation, pressure, humidity and wind speed; aggregated to 6 hourly) were derived from the water and global change forcing data era-interim (WFDEI; [62]). Atmospheric CO_2 concentrations were kept at the current level (i.e. 370 ppm) to avoid CO_2 fertilization effects. Cropland areas and growing seasons were derived from the monthly irrigated and rainfed crop areas around the year 2000 (MIRCA2000; [30]), and included up to three crop growing seasons. Crop growing season onset and length were subsequently calibrated (within the limits of MIRCA2000) to ensure optimal crop production. Several adjustments were made to the reported growing seasons. The second season rainfed rice in China and Japan were omitted, as rice was grown during months where crop growth could not occur due to low temperatures. The first irrigated wheat season in China was extended, as other sources [63, 64] reported longer growing seasons that were more in line with the reported national crop production. Further

setup information is given in supplementary information S.2.

3. Results

3.1. Production gaps

First total (rainfed plus irrigated) production gaps were analyzed, to put irrigated production gaps into context. Potential worldwide total (rainfed and irrigated) wheat, maize, rice and soybean production was estimated at 1228 (±34; detrended interannual standard deviation), 1257 (±35), 664 (±17), and 188 (±3) Mt y^{-1}. However, due to water and nutrient limitations, wheat, maize, rice and soybean can achieve only 54%, 63%, 93%, and 95% of their potential production under baseline conditions (figure 2). Also, under baseline conditions the detrended interannual standard deviations of wheat, maize, rice and soybean increase to 3%, 3%, 2%, and 8% of their production respectively, resulting from increased year-to-year variability in rainfed water availability. To quantify the limitation from water and nutrients for these production gaps, we compared various simulations. Rainfed crop water limitations were assessed by comparing the potential and attainable simulations, and nutrient limitations were assessed by comparing the attainable and baseline simulations. Irrigated crop nutrient limitations were assessed by comparing the potential and baseline simulations (irrigated crops were assumed not water limited). 86% of simulated baseline wheat production gaps were limited by water (483 Mt), while 68% of maize production gaps were limited by nutrients (315 Mt). Rice is mostly nutrient limited due to the extensive paddy rice irrigation, and soybean is mostly water limited due to its ability to fix nitrogen.

3.2. Irrigation constraints

Irrigated production gaps are notably smaller due to increased crop water availability through irrigation. Simulations indicate irrigated wheat, maize, rice and soybean can achieve 89%, 80%, 95%, and 100% of their potential production under baseline conditions (table 2). Hence, opportunities to increase worldwide irrigated crop production through increased nutrients supply are relatively limited, and would require a 20% nitrogen uptake increase (from baseline 19 Mt y^{-1} to a potential 22 Mt y^{-1}).

Accompanying baseline worldwide irrigation withdrawals were estimated at 2881 (±84; interannual standard deviation) km^3 y^{-1}. Under nutrient gap closure, for the irrigated crops considered here, irrigation withdrawals would increase by only 3% (to 2969 km^3 y^{-1}). However, more than one third (34% or 987 km^3 y^{-1}) of the baseline irrigation withdrawals is considered to be unsustainable. These withdrawals come at the expense of environmental flows or from non-renewable water resources (figure 3).
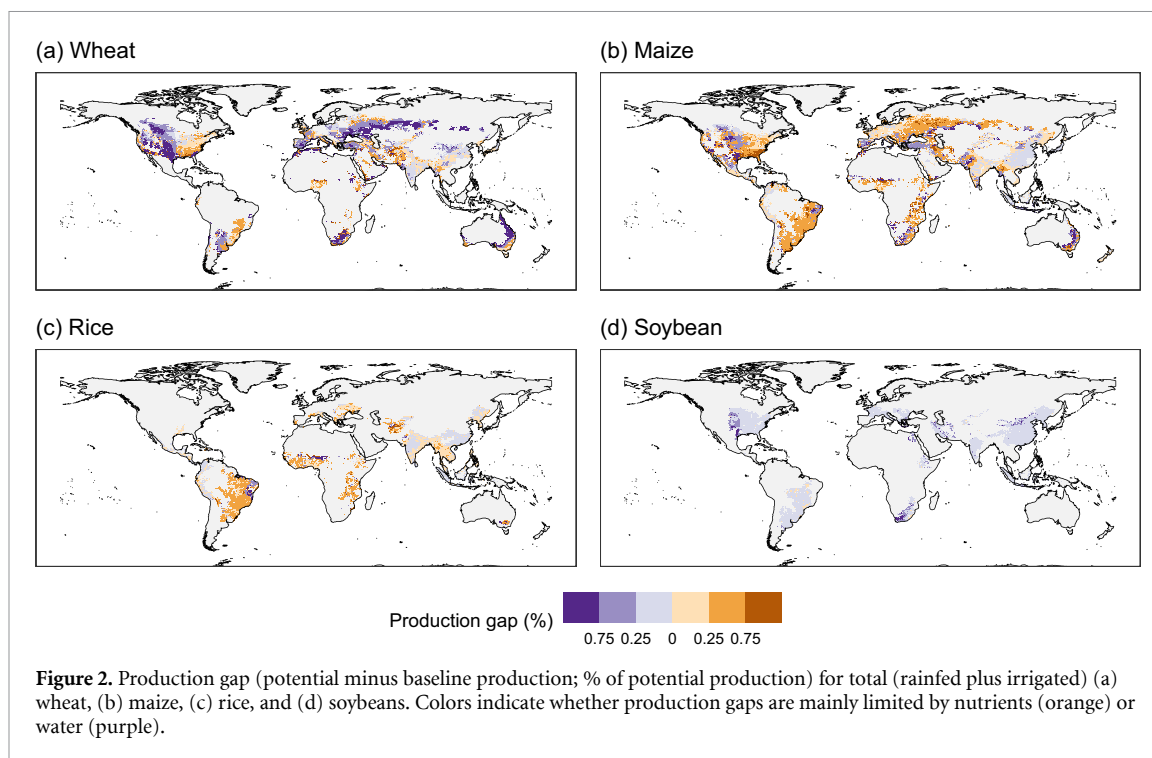
Figure 2. Production gap (potential minus baseline production; % of potential production) for total (rainfed plus irrigated) (a) wheat, (b) maize, (c) rice, and (d) soybeans. Colors indicate whether production gaps are mainly limited by nutrients (orange) or water (purple).

Table 2. Worldwide irrigated wheat, maize, rice and soybean crop production for potential, baseline, attainable and restricted simulations.

Crop production	Potential (Mt y^{-1})	Baseline (Mt y^{-1}) (% of potential)	Attainable (Mt y^{-1}) (% of potential)	Restricted (Mt y^{-1}) (% of potential)
Wheat	268	238 (89)	208 (78)	190 (71)
Maize	242	193 (80)	194 (80)	162 (67)
Rice	436	412 (95)	399 (91)	381 (87)
Soybean	15	15 (100)	14 (94)	14 (94)
Total	961	858	815	747

Unsustainable water withdrawals are mostly concentrated in several regions such as: Pakistan and northwestern India (combined 32% of total), southern United States and Mexico (combined 24% of total), and Spain, Iraq, Iran and northeastern China (combined 12% of total). These regions are well-known for their groundwater exploitation [18, 19, 65–69], and environmental flow transgression [22, 28, 70].

3.3. Attainable irrigated crop production
Attainable irrigated crop production was estimated by constraining unsustainable irrigation withdrawals and at the same time increasing nutrient application up to nutrient gap closure requirements. Under these conditions, worldwide irrigated wheat, maize, rice and soybean production was estimated to change by −12.6, +0.3, −3.3, and −6.2% (−30, +1, −14 and −1 Mt y^{-1}) compared to the baseline (table 2). This decrease can be divided into a total (all crops) 13% decrease in production due to decreased water availability (baseline to restricted production), and a 8% increase due to increased nutrient application (restricted to attainable production). Worldwide

maize and rice production was reduced the least, as the increase in nutrient application offset their baseline nutrient limitations (section 3.1). Worldwide wheat and soybean production was reduced more substantial.

The previously mentioned regions with high levels of unsustainable water withdrawals (section 3.2) would show also large crop production reductions, when comparing the attainable production to the baseline (figures 4 and 5). Estimated maize and wheat production reductions would be mostly concentrated in the irrigated croplands of northeastern China (Hai, Huai and Yellow river basin). This region would cover 44% of both worldwide maize and wheat reductions. Furthermore, these reductions constitute to almost a quarter of the region's baseline production. Reduced rice production would mainly occur in the irrigated croplands of Pakistan and northwestern India (Indus and Ganges river basins). These reductions would cover an estimated 32% of worldwide rice reductions and more than a third of the region's baseline production. The southern United States
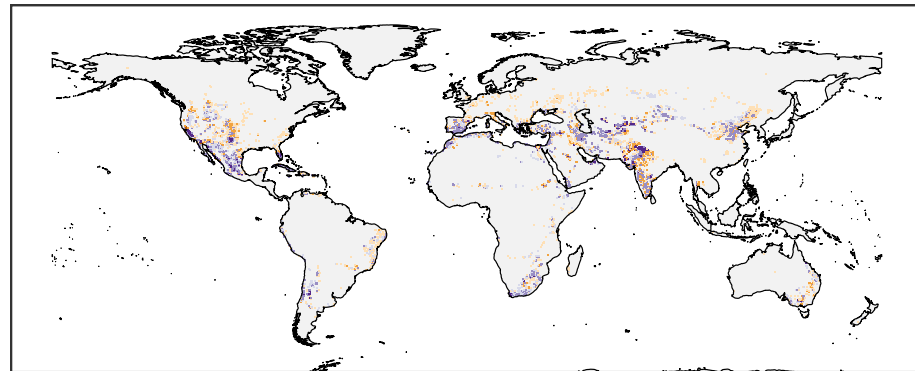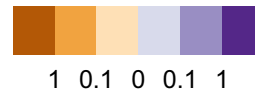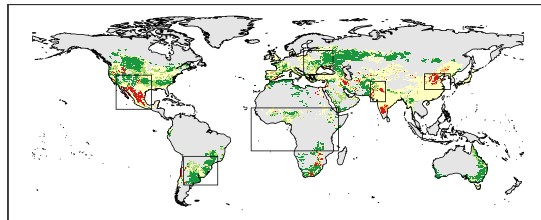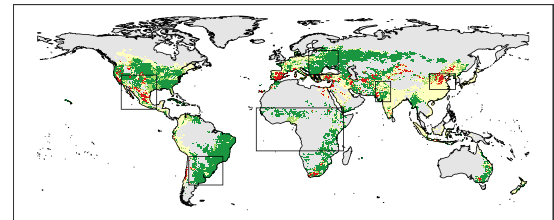
Figure 3. Water gap (unsustainable withdrawals) for irrigation under production gap closure. Colors indicate whether water gaps are mainly at the expense of environmental flows (orange) or environmental flows and non-renewable water resources (purple).
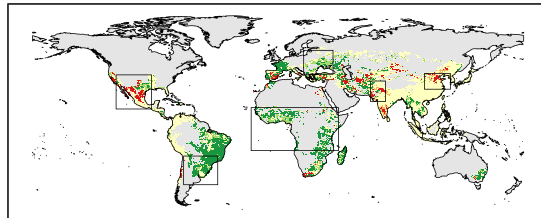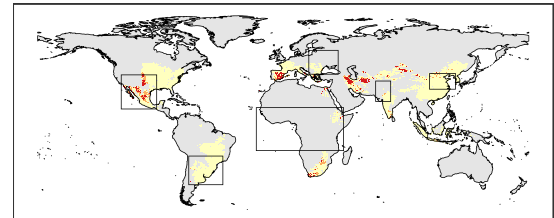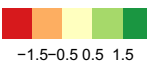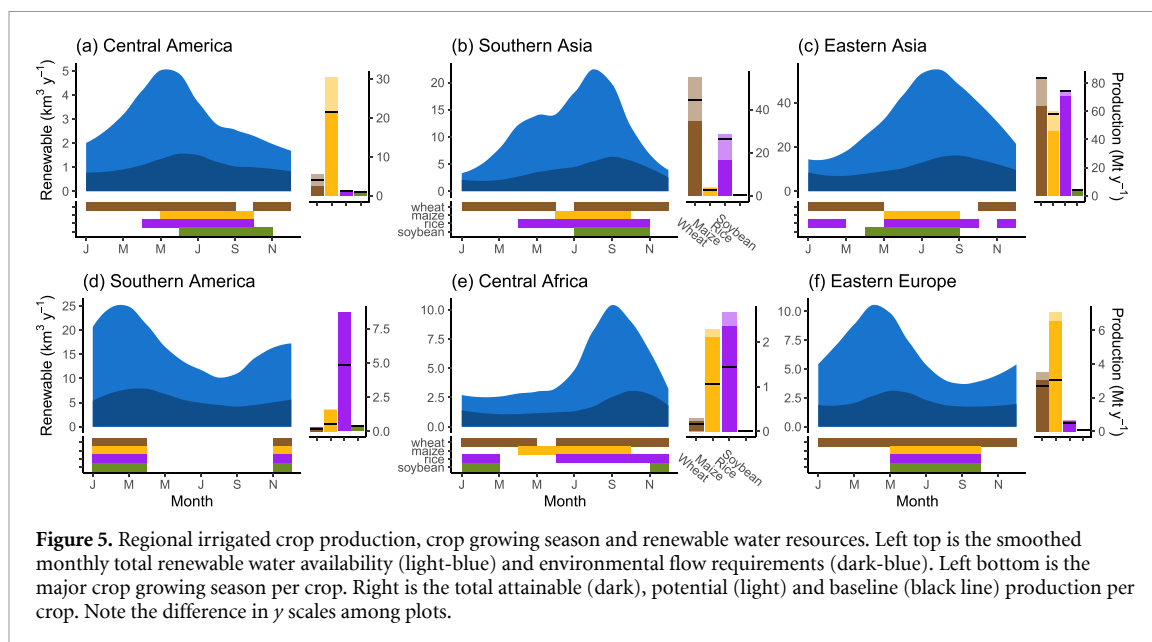

Figure 4. Crop yield changes for irrigated (a) wheat, (b) maize, (c) rice and (d) soybeans between baseline and attainable simulations. Boxes indicate the areas used in figure 5.

and Mexico (Mississippi, Colorado and Rio river basins) would be responsible for 24% of worldwide soybean reductions (23% of its baseline soybean production).

On the other hand, regions such as southern America, eastern Europe, and central Africa may sustainably increase their baseline irrigated crop production. These regions still have a nutrient gap to exploit and, especially for southern America, irrigated crops were mostly cultivated during periods of high renewable water availability. As such, sus-

tainable intensification on irrigated croplands may achieve increases of 79% for rice in southern America, 97% and 63% for maize and rice respectively in central Africa, and 114% for maize in eastern Europe. However, currently these regions contribute only little to the worldwide irrigated crop production, as their irrigated area is limited. These results indicate possibilities to sustainably expand irrigation in these areas. However, quantifying the sustainable expansion extent lies outside of the scope of our study.

Figure 5. Regional irrigated crop production, crop growing season and renewable water resources. Left top is the smoothed monthly total renewable water availability (light-blue) and environmental flow requirements (dark-blue). Left bottom is the major crop growing season per crop. Right is the total attainable (dark), potential (light) and baseline (black line) production per crop. Note the difference in *y* scales among plots.

4. Discussion

Our study aims to quantify the impact of worldwide water constraints on attainable irrigated crop production. Attainable production accounted for increases in nutrient application, while limiting irrigation withdrawals to renewable water availability and without compromising river ecosystem water requirements. The quantification of attainable irrigated production was made possible by our newly developed model framework, which fully (two-sided) couples the VIC hydrological model and the WOFOST crop model. This model framework is the first to simulate daily biophysical processes related to worldwide water availability and crop growth under various water and nutrient limitations. This framework enabled our study to comprehensively simulate attainable irrigated crop production under sustainable intensification. Our simulations demonstrate limited possibilities to increase irrigated crop production through additional nutrient application. However, at least one third of current irrigated water withdrawals need to be reduced in order to account for environmental flow requirements and renewable water availability. Under these water constraints, substantial increases in worldwide irrigated production cannot be achieved.

Our study examined attainable irrigated crop production in terms of water quantity constraints. However, other considerations regarding sustainable intensification fell outside our study scope. Increasing production and optimizing management may not be viable due to socioeconomic constraints such as marginal investments returns, poor access to markets, and increased labor requirements [5, 71]. Also, increasing nutrient application rates without improving nutrient management practices have adverse side effects such as increased greenhouse gas emissions,

river eutrophication, and coastal hypoxia [72–75]. The quantification of attainable irrigated production was affected by several limitations. Most importantly, the worldwide extent of our study required the use of coarse and aggregated input data (e.g. weather, soil, land-use, and fertilizer). These inputs hide the inherent local variation of agricultural processes which may interact non-linearly with crop growth [76–78]. These datasets also carry their own uncertainties due to data limitations [9, 30, 55, 56, 79]. Sensitivity analysis (Appendix B) indicated that, at our resolution, production was most sensitive to the timing and length of the growing season. The growing season was subsequently calibrated. However, at higher resolutions other aspects such as geohydrology, soil quality, fertilizer gradients and cropping patterns may become more apparent. Also, crop cultivar parameters other than phenology parameters (e.g. distribution of dry matter, optimum nutrient content, and translocation fractions) were kept constant for each crop. Therefore they do not comprehensively reflect the crop varieties cultivated worldwide [80]. Further locally-oriented research (using locally relevant and high resolution observations) is needed to address these limitations and confirm the results of our study.

Our simulated worldwide crop production falls within the range of other studies (supplementary table S.3; [3, 9, 81, 82]). This is also the case for simulated irrigation withdrawals (supplementary table S.4; [24, 83–87]). The delineation and quantification of unsustainable irrigation withdrawals is similar to Rosa *et al* [29] and Jägermeyr *et al* [28], who also explored possibilities for irrigation intensification. In line with our work, both studies also show that sustainable intensification of crop production on currently irrigated croplands is limited. However,

our study indicates that the decrease in crop production under sustainable irrigation management can be offset by increased nutrient application. Substantial increases in irrigated crop production can be achieved locally through the increased availability of nutrients. Nevertheless, even when accounting for increased nutrient application, water constraints resulting from sustainable irrigation management would result in a net decrease in worldwide crop production by 5%. This decrease is largely due to reduced water availability in some of the largest irrigated cropland areas worldwide, which currently use unsustainable irrigation practices. It is important to acknowledge that some of the areas with unsustainable irrigation practices (e.g. Pakistan, India, and China) have large populations and are striving to achieve food security through various degrees of self-sufficient agricultural production [88–90]. In order to achieve sustainable crop production increases for these irrigated croplands, options other than intensification should be explored such as: reducing irrigation demands by changing to less water intensive crops and developing water efficient crop varieties [5, 91], reducing irrigation withdrawals by increasing the irrigation efficiencies [28, 92], increasing irrigation availability through inter-basin water transfers [93], and reallocating and expanding irrigation use in areas where sufficient water is available [29, 94, 95]. Moreover, climate change and socio-economic developments should be considered, as they will affect agricultural production through agricultural adaptation and CO_2 fertilization [96–99], and available water resources through precipitation and sectoral water demand changes [23, 100–102].

Ultimately, nutrient and water limitations are not the only factors influencing food security, as food security is a complex combination of biophysical factors, access, economics, and consumption and production patterns [4, 6, 103–105]. However, our results imply that intensification of currently irrigated croplands is at odds with sustainable water management. The question remains how long current unsustainable practices (e.g. groundwater exploitation) will remain physically, economically and environmentally feasible to support irrigated crop production [106–109].

5. Conclusion

Irrigated wheat, maize, rice and soybean production gaps on currently irrigated croplands range from 83% to 100% of their potential. Achieving potential production would require an estimated 20% increase of crop nitrogen uptake. However, in order to satisfy environmental flow requirements and avoid non-renewable water withdrawals, current irrigation withdrawals should be reduced by at least one third according to our simulations. Under these water constraints, substantial increases in achievable irrigated

production cannot be attained, even when considering increases in nutrient application. On the contrary, a change of −30, +1, −14 and −1 Mt y^{-1} is estimated for achievable irrigated wheat, maize, rice and soybean production respectively. The majority of these losses are concentrated in extensively irrigated cropland areas (e.g. northeastern China, Pakistan, and northwestern India). Sustainable intensification is possible on irrigated croplands in regions such as southern America, central Africa and eastern Europe. However, in these regions only a small fraction of crop is irrigated, and thus their contribution to worldwide irrigated crop production is limited. In sum, attainable irrigated production under worldwide water constrains is 78%, 80%, 91%, and 94% of the potential wheat, maize, rice and soybean production respectively.

Appendix A. Model performance

To assess our model performance, simulated national annual crop production was compared to food and agricultural organization (FAO) reported values [112]. Simulated crop production is well represented over a large range of climate and soil classifications (correlation larger than 0.9 for all crops), as seen in figure A1. However, simulated crop production was generally higher than reported (see also supplementary figure S.1 and table S.2). This was expected since the model was explicitly not calibrated to account for sub-optimal crop production practices (section 2.2). Overestimations generally reduce

Figure A1. Comparison between FAO reported [112] and simulated national annual total (irrigated and rainfed) (a) wheat, (b) maize, (c) rice and (d) soybeans production. Error lines indicate the detrended interannual variation (one standard deviation). Simulated crop production has been adjusted for differences in harvested area. Note the plots are on a log-log axis to better display the large range of values, and that the plot axis vary for each crop.

over time as agricultural production is optimized (also called the technological trend [113]). On the other hand, underestimations are found in maize production, especially in the Americas (figure A1(b)). Underestimations are mostly related to water stress factors in the Argentinian Pampas and the United States Midwest. Simulated water stress in these areas is probably higher due to shallow groundwater tables in these areas [114, 115] that are not well simulated by our model framework.

Appendix B. Sensitivity analysis

Simulated worldwide irrigated crop production sensitivity was analyzed for changes in growing season, soil characteristics, and nutrient and water inputs. Crop production was estimated for: (a) short (25th month day of planting to 5th month day of harvest) and long (5th month day of planting to 25th month day of harvest) growing season length, (b) early (5th month day for planting to 5th month day for harvest) and late (25th month day for planting and 25th month day for harvest) growing season timing, (c) high (+25%) and low (−25%) fertilizer application, (d) high (+25%) and low (−25%) mineralization rate, high (+25%) and low (−25%) irrigation efficiency, and high (+25) and low (−25) soil

sand percentage (subsequently influencing soil characteristics such as hydraulic conductivity and available water content). Most factors were assessed for the baseline simulation. However, the irrigation efficiency and soil sand content were assessed for the attainable simulation, as this simulation limits water withdrawals (and not nutrient availability). Supplementary figures S.4 to S.9 indicate the spatial distribution of the sensitivity.

The growing season length is the dominant factor for changes in simulated crop production (table B1). In general, longer growing periods can lead to higher biomass assimilation and thus higher crop production, as is the case for both soybean and rice. However, growing seasons are also determined by the water and nutrient availability during the growing season. Maize is mostly nutrient limited (see section 3.1), and shorter growing periods are often preferred to avoid nutrient deficits. This is accompanied by a strong response to fertilizer application and mineralization. Wheat is mostly water limited (see section 3.1), and is also sensitive to the timing of the growing period. Shifted growing periods can avoid early or late droughts that may affect crop production. Irrigation efficiencies and soil characteristics mostly affect the irrigation water demands. However, the water constraints imposed in this study are generally larger than the reduction in irrigation water demands. As

Table B1. Simulated crop production variation (% of baseline or attainable production) for changes in growing season length, growing season timing, fertilizer application, mineralization rate, irrigation efficiency, and soil characteristics.

Category	Wheat variation (%)	Maize variation (%)	Rice variation (%)	Soybean variation (%)
Season length	34	51	23	13
Season timing	26	37	7	7
Fertilizer application	11	20	6	0
Mineralization rate	6	11	6	0
Irrigation efficiency	2	2	1	1
Soil characteristics	2	4	3	1

a result attainable irrigated crop production (i.e. the crop production under constrained water withdrawals) is affected to a lesser extent.

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