We would like to thank this reviewer for his/her comments and suggestions. We are convinced that incorporating the proposed revisions will significantly improve the quality of the paper. Specific replies to the reviewers questions and comments can be found below (in italic).

Anonymous Referee #1
Received and published: 15 September 2015

The paper describes an analysis of seasonal irrigation water requirements and crop productivity in South Asia. The region is highly populated and irrigation essential to ensure the supply of the growing population with food. The climatic conditions are very diverse with deserts in the west, very humid conditions in the east, the Himalaya Mountains in the North and fertile lowlands along the major rivers. In addition, interannual variability in precipitation is high because of the varying strength of the monsoon. Therefore, cropping patterns in this region are very complex as well with highly intensive land use enabling three or four crop harvests per year and extensive land use including fallow land on the other hand. Assessments of crop water requirements and crop productivity need to account for this diversity and complexity which is challenging. Therefore contributions such as the present manuscript are welcome and fit well to the scope of the journal. The manuscript is well written and interesting.

Thanks

However, several aspects require attention and major improvements are required before I may recommend the manuscript for publication in HESS:

Major comments: 1) While the methodology presented in this article is interesting and innovative, the analysis of the obtained results and the discussion and comparison with other research require improvement. The simulation of seasonal crop water requirements and corresponding impacts on crop yields for South Asia itself is not new. The MIRCA2000 dataset explicitly accounts for multiple cropping practices in South Asia and has been applied in many assessments and modelling studies, e.g. by Siebert and Doell (2010). The FAO provides crop calendars for the region which also account for multiple cropping and which were applied to simulate irrigation water requirement and withdrawal at daily time steps (Hoogeveen et al., 2015; Frenken and Gillet, 2012).

We acknowledge that there are other models that incorporate the effects of multi cropping on irrigation water requirements and will add references to the mentioned studies in the introduction. Both studies however have a different focus and do not show the results for seasonal irrigation demands at the level of detail as analysed in this study.
Hoogeveen et al. include multiple cropping as they incorporate national level FAO cropping calenders. They do not report on seasonal irrigation demand, but reference to their total calculations for South-Asia (910 km3 per year, table 7) will be included in the validation table (table 1).
Siebert an Doell (2010) use the same land use data (MIRCA2000) as this study and also incorporate MIRCA cropping calenders and the effect of multi cropping. They do report on global seasonal irrigation demand (fig 6), but not for the South Asian crops specifically. We will add this reference in the introduction and refer to their results for irrigation water demands and crop production for South Asia in the validation and

discussion.
References to the results of Hoogeveen et al (2015) and Siebert and Döll (2010) have been added to the introduction, line 17-22.
Estimates for irrigation water consumption and withdrawal have been added in table 1.

An advancement in the current study is certainly that it accounts for spatial patterns in the begin of the monsoon season and the corresponding Kharif cropping season. Water requirements and crop production are then presented per season to highlight the impact of the seasonal variability in climate conditions on water requirements, drought stress and corresponding crop yields. Therefore, to demonstrate the scientific merit of the current study it is essential to compare the results obtained with the improved version of the model and input data with results obtained by not explicitly accounting for multiple cropping practices in the region (versions and setup of LPJmL used in previous research).

For comparison, we will make one additional model run with the version of LPJmL as used in previous research (single cropping season and simulated sowing dates as in Biemans et al. 2013) but with the same climate forcing as used in this study. We will add the resulting daily irrigation demand in figure 5 and discuss.
LPJmL was run with the single cropping landuse input as in previous model studies by the authors (Biemans et al, 2013) and sowing date was determined based on climate as in Waha et al (2012). Resulting calculated daily mean irrigation water demand was added to figure 5 and the comparison is now mentioned in the discussion (part 4, line 11)

2) The model was calibrated against crop yields observed during the period 2003-2008 by using three parameters: maximum LAI, maximum harvest index and a parameter scaling leaf biomass to plot level (section 2.4). Therefore it is not surprising that crop yields simulated by the model matched the observations after calibration (page 7852, lines 13-14; Figure 4). This shows that the calibration was successful but it is not a proof for the accuracy of the model itself. A validation of the model should be based on data not used for the calibration.

Reviewer is right here. We will remove this sentence which states that the calibrated crop yields match the observations as this is straightforward. We will replace this by a note marking that calibration of management factors per state enables us to simulate heterogeneity of yields between states and regions (which is illustrated in figure 4).
Done as proposed.

In addition, calibrating the model for crop yields does not mean that simulated crop water requirements are accurate as well. In particular the adjustment of the LAI parameter in the calibration for crop yield will affect crop transpiration. Consequently it can happen that a higher accuracy of simulated crop yields is on the expense of less precise results for crop water use. Therefore, more comparisons to national or subnational data for irrigation water requirements or irrigation water supply would be helpful. This could include results from model runs without the improvements made for this study to demonstrate the advancement achieved with the new version. I would expect, that in particular the estimates of the contribution of the different water sources to irrigation improved due to the model improvements presented in this study.

We will add a comparison with results of the previous model version (with single *cropping and different sowing dates), see also previous comment.*

Done as proposed, see previous comment

Moreover, we will compare our results with subnational statistics for groundwater extractions for Indian states and with subnational estimates of irrigation consumption provided by Siebert et al (2010) in HESS (Groundwater use or irrigation – a global inventory) and discuss differences.

We have added more comparisons with other estimates (mainly Siebert et al) in table 1. However, we have decided not to present subnational calculations for groundwater extractions here for two reasons:

1 the focus of the paper is seasonal estimates of irrigation water demand, not yet a comparison with availability. We are afraid that the paper gets more chaotic and more unclear if this validation is added as it distracts from the main message and purpose of the paper.

2 although we hint towards a next paper where we will do proper comparison of water demand by crop and water supply by source, the current architecture of the model is not yet ready to make that analysis properly. Although we make a rough estimate of ground and surface water supply at national and basin level, it feels uncomfortable to present those estimates with more detail. A follow up study will hopefully address this questions in an improved way.

The reviewer is right about the effect of the maximum LAI parameter on the transpiration and irrigation water requirements. Generally, crops with high management factor will have higher yields and higher transpiration but lower soil evaporation, which we believe is realistic. We will test the effect of our calibration on the estimate of total irrigation water demand and add this to the discussion.

The effect of calibrated management on total irrigation requirements has been tested. Results are presented and discussed in the discussion part of the paper.

Specific comments:

Page 7845, line 28: please use “multiple cropping” consistently throughout the manuscript (in the current version it is sometimes multi-cropping, sometimes multiple cropping)

We will check the manuscript carefully for any inconsistent use of terms and make sure that the terms are used uniformly.

We have changed all occurences of the term ‘multi-cropping’ into multiple cropping.

Page 7849, lines 11-14: “Crop classes in MIRCA2000 were first aggregated to the crop classes available in the LPJmL model, which are fewer (12, irrigated and non-irrigated, plus one class with “other perennial crops”, vs. 26 in MIRCA) but include the most important food crops for South Asia (see Fig. 2 for distinguished crops).” => How did the authors treat crops not shown in Fig. 2, for example barley or cotton? Are water uses of these crops included in the totals reported by the authors (e.g. in Table 1) or not? If not, it is necessary to mention this, e.g. when comparing to total water uses simulated or estimated in other studies.

Crops not shown in figure 2 are included in two classes ‘other crops’ treated either as seasonal (e.g. potatoes) or perrenial crops (e.g. tree crops). Water uses of these crops are thereby included in the totals reported. A note that clarifies this will be added to the text.

Figure 2 caption already stated that “Temperate and tropical roots and sunflower are not shown because they occupy relatively small areas; other perennial crops are not shown because there are no statistics available”

Page 7851, line 17: “and a “summer” season from April to May.” => This season is typically called Zaid season.

We will refer to ‘Zaid season’ in the text, but since we do not explicitly simulate the short growing Zaid crops, and crop water demand during this period is mainly from perennial crops like sugarcane and other perennial crops (see figure 5), we prefer to use the term ‘summer’ throughout the text and in the figures.
We decided not to mention the name of the this Zaid season in the text, as it might raise confusion.

Page 7853, lines 4-6: “Irrigation efficiency for canal water was estimated at 37.5% in India, Bangladesh, Nepal and 30% 5 in Pakistan (Rohwer et al., 2007); efficiency of groundwater irrigation was estimated at 70% for all countries (following Gupta and Deshpande, 2004).” => This belongs to Material and methods but not to the Results section.

We will move these lines to the Material and Methods section.
Done as proposed

Section 3.3: How do the seasonal estimates compare to those recently described in Smilovic et al. (2015)?

Smilovic et al (2015) study focusses on wet and dry rice and wheat. In their paper they present estimates of irrigated and rainfed kharif rice and rabi wheat production for all Indian states, These production figures will be compared to our results as well as the relative contribution of rainfed and irrigated fields to this production. A reference to this study will be included.
A short comparison with the study of Smilovic et al was added in section 3.3

Page 7856, lines 8-9: “Incorporating seasonal cropping patterns in more detail leads to improved estimation of the timing of water demand.” => This I also would expect but better would be to proof it by comparison to simulations with the previous model version.

See earlier comment. We will add the daily water demands simulated by the version and settings as used in previous research for comparison.
Comparison to a run without double cropping and with other determination of sowing dates was included in figure 5.

Page 7858, lines 7-8: “gross irrigation demand during the Rabi season is _ 30% lower than during the Kharif season, the traditional cropping season.” => Shouldn’t it be higher (see line 14 on the same page)?

Yes, the reviewer is right. We will correct this.
Corrected as proposed

References:
Frenken K., Gillet V. (2012) Irrigation water requirement

and water withdrawal by country. FAO, Rome, Italy, 263 pp., http://www.fao.org/nr/water/aquastat/water_use_agr/IrrigationWaterUse.pdf

Hoogeveen J., Faurès J. M., Peiser L., Burke J., van de Giesen N. (2015) GlobWat – a global water balance model to assess water use in irrigated agriculture. Hydrol. Earth Syst. Sci., 19, 3829-3844

Siebert S., Döll P. (2010) Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. Journal of Hydrology, 384, 198-217.

Smilovic M., Gleeson T., Siebert S. (2015) The limits of increasing food production with irrigation in India. Food Security, 7, 835-856.

We would like to thank this reviewer for his/her comments and suggestions. We are convinced that incorporating the proposed revisions will significantly improve the quality of the paper. Specific replies to the reviewers questions and comments can be found below (in italic).

Anonymous Referee #2
Received and published: 24 September 2015

Dear Editor and Authors,
I have read the draft article by Biemans et al. closely. My comments are summarized below. Hope some of them are useful for making decision and further revisions.

General comments

The authors applied the LPJmL global hydrological model to four nations in South Asia. They added some new numerical schemes and data to express multiple cropping in LPJmL and quantified irrigation water consumption and withdrawal by season (the wet season called Kharif and the dry season called Rabi), type of crops, and source of water (surface or groundwater). They found the seasonality in irrigation water demand and abstraction is remarkable in the region.
In the Asian Monsoon region, farmers drastically change the type of crops and application of irrigation for periodical wet and dry seasons. Although the practice is common for millennia in Asia, neither systematic datasets nor comprehensive macro-scale hydrological models are yet available, particularly on water use. The work presented here would potentially contribute to this field.
I found the draft is well prepared, but for further clarity, additional information is required at some points. The details are commented below.

Specific comments

Page 7850 Line 28 “Normal onset dates of the monsoon over South Asia are determined by the India Meteorological Department (IMD). . .”: What is the primary factor to determine the onset? Is the factor (e.g. rainfall) consistent between WFDEI and IMD? In other words, is the discrepancy of data between WFDEI and IMD negligible? Another point is that the onset varies year by year. Did the authors use the year-specific onset date in the simulation period or fix throughout the period? If latter is the case, what would be the potential impacts to the results?

The sowing dates were kept constant during the whole simulation period and based on average monsoon onset dates. The IMD bases their determination of onset on a combination of certain rainfall, windspeed and outgoing long wave radiation characteristics. Potentially there is an mismatch between the WFDEI and the IMD year specific monsoon onset dates, but because of the combination of factors it is not straightforward to determine whether there is a mismatch between the WFDEI and the IMD reported onset.
This IMD map was used to determine grid specific input data for the sowing date of kharif crops, and this sowing date is –despite of an eventual mismatch of few days- a major improvement compared to the previous version of the model, with only one cropping period which was not related to timing of monsoon.
We will mention this issue as an uncertainty in the discussion of the revised version of the paper. We will also briefly discuss potential impacts on the results.
Few lines about this uncertainty and year to year variation in monsoon onset are inserted in the discussion of sowing dates.

Page 7851 Line 21 “represented by three parameters: maximum leaf-area index, maximum harvest index and a parameter that scales leaf-level biomass production to plot level”: What is “plot level”? What does “scale” mean? What kind of “management” is represented by this parameter? Similarly, perhaps it might be informative for readers to note that the maximum LAI and harvest index represent cropping density and adoption of high-yield crop species respectively.

The calibration procedure of LPJmL was developed by Fader et al. (2010) and applied here. Plot level in this context means the total area of the crop within the gridcell, a plot shares the same climate, soil and landuse. “Scale” means that a yield reduction has been applied to translate from biomass production of individual plants to plot level. Fader (2010) explain this as follows: “The assumption is that intensively managed crop stands (LAImax = 7) have little or no areas with reduced productivity (α–a = 1.0) due e.g. to poor soil conditions or pests and diseases, while such areas are more common in extensively managed crop stands (LAImax = 1; a–a = 0.4).” We will add a note that the three parameters are related to crop density, crop varieties and the occurrence of poor soils, pest and diseases respectively.
The procedure for calibration was extended with this extra note on the physical interpretation of the different calibration parameters. For a more detailed description the reader is referred to the original paper by Fader et al. (2010)

Page 7852 Line 5 “We used 5 year average yield statistics, for 2003-2004 till 2007-2008”: First, the calibration period seems overlapping with the simulation period (page 7848 line 24). If this is the case, note clearly that calibration and validation periods are same in this study, particularly where the performance of simulated crop yield is discussed. Second, “5 year average yield” indicates that the model performance on inter-annual variation of crop yield (i.e. the crop yield response to change in meteo-rological condition) was not validated. Without this, it should be difficult to justify the reliability of comparison of crop yield between with and without irrigation (e.g. Page 7855 Line 17).

We will add a note to clarify that figure 4 reflects the result of a calibration and that there was no separate validation (we do not refer to validation in the text).

As this remark was also made by reviewer nr 1, we deleted a sentence stating that calibrated crop yields agreed well with observed crop yields (as this is straightforward) and replaces this by a sentence emphasing more that with state level management factors, we are able to simulate better the existing spatial heterogeineity in crop yields between diffemrent regions in South Asia.

In this study we compared the multi-year average. We did indeed not validate the crop yields from individual years, which would be a good addition to the study. This is actually done in a second, connected paper (Siderius et al, in review), which specifically focusses on the impact of inter-annual variability. We will added a reference to this paper in the discussion and will shortly highlight what are the consequences. Despite the lack of an inter-annual comparison we do think the current approach justifies the here presented comparison.

A reference to the study by Siderius et al, that is now in press, is added to the description of calibration results. The reader is referred to that paper for a detailed analysis of year to year yield variations in yields (and irrigated area) at *district, state and national level.*

Page 7856 Line 26 “Use of residual soil moisture from one season to the other was not incorporated in this way”: Another possible factor is abstraction of river water in upstream: simulations separating Kharif/Rabi exclude this factor, hence the estimated surface water availability could be overestimated.

The reviewer is right here, although within the two simulations the effect of upstream abstractions is reflected in downstream availability. Simulating double cropping of a range of crops with different planting dates in a single integrated model run was not a feature of the LPJml model, or most global hydrology-vegetation models. We are further developing the model and in a next version we plan to fully integrate a double cropping module, which allows us to relate all withdrawal to source of supply in a totally consistent way.

Figure 5: Would it be possible to add a same graph for water source? It would be helpful (and hopefully interesting) to visualize the seasonal march of dominant water source from surface water to groundwater and vice versa.

An estimate of the seasonality of surface water and groundwater supply per basin is given in figure 7. Unfortunately, model architecture does not yet allow for fully integrated model runs with double cropping and therefore a detailed figure as figure 5 can not yet be provided yet We are working towards a version that will make this analysis possible. (see also previous comment).
I hope the reviewer is satisfied with the coarse estimate of surface and groundwater supply to irrigation as presented in figure 7. A detailed figure with day to day supply by source is not yet possible but under development. This paper mainly focusses on the improvement of water demand calculations.

Crop-specific seasonal estimates of irrigation water demand in South Asia

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Abstract

Especially in the Himalayan headwaters of the main rivers in South Asia, shifts in runoff are expected as a result of a rapidly changing climate. In recent years, our insight in these shifts and their impact on water availability has increased. However, a similar detailed understanding of the seasonal pattern in water demand is surprisingly absent. This hampers a proper assessment of water stress and ways to cope and adapt. In this study, the seasonal pattern of irrigation water demand resulting from the typical practice of multiple-cropping in South Asia was accounted for by introducing double-cropping with monsoon-dependent planting dates in a hydrology and vegetation model. Crop yields were calibrated to the latest state-level statistics of India, Pakistan, Bangladesh and Nepal. The improvements in seasonal land use and cropping periods lead to lower estimates of irrigation water demand compared to previous model-based studies, despite the net irrigated area being higher. Crop irrigation water demand differs sharply between seasons and regions; in Pakistan, winter (Rabi) and summer (Kharif) irrigation demands are almost equal, whereas in Bangladesh the Rabi demand is ~100 times higher. Moreover, the relative importance of irrigation supply versus rain decreases sharply from west to east. Given the size and importance of South Asia improved regional estimates of food production and its irrigation water demand will also affect global estimates. In models used for global water resources and food-security assessments, processes like multiple-cropping and monsoon-dependent planting dates should not be ignored.

1. Introduction

As global demand for food increases, water resources – one of the main resources for producing food – are becoming increasingly stressed. South Asia, home to ~25% of the world population, is often identified as one of the future water-stress hotspots (Kummu et al., 2014; Wada et al., 2011). Excess food production in recent years has obscured this bleak future; increases in both agricultural productivity and cropland extension have made the region food self-sufficient in its staple crops in recent decades. But the resources that supported this increase – surface- and ground- water extracted for irrigation, land converted into cropland, increased use of nutrients and pesticides – are not unlimited. Groundwater levels are already falling rapidly in large parts of South Asia due to overexploitation (Rodell et al., 2009; Tiwari et al., 2009) and surface-water irrigation is reaching its limits (Biemans, 2012), costly river interlinking schemes aside (Bagla, 2014; Gupta and Deshpande, 2004a). On top of this, higher temperatures and an expected higher variability in climate due to global warming further jeopardizes future food production in the region (Krishna Kumar et al., 2004; Mall et al., 2006; Moors et al., 2011).

In order to understand if, when and where water availability to sustain crop production becomes critical, a more thorough understanding of the potential mismatch between seasonal water availability and demand is required. In recent years, our insight in the seasonal pattern of water availability has increased due to a better understanding of fluctuations in monsoon onset (Goswami et al., 2010; Kajikawa et al., 2012; Ren and Hu, 2014), and the variation in the active-break cycle of the monsoon, which governs intra-seasonal droughts (Joseph and Sabin, 2008), both influenced by large-scale phenomena like El Nino (Joseph et al., 1994). Effort has also gone into quantifying the seasonal availability of snow and glacier melt runoff on the regional scale (Bookhagen and Burbank, 2010; Siderius et al., 2013a), with intra-annual shifts in runoff expected in the future due to climate change (Immerzeel et al., 2013; Lutz et al., 2014; Mathison et al., 2015; Rees and Collins, 2006). When it comes to estimating water demand, however, a similar detailed understanding of the seasonal pattern is surprisingly absent.

Two essential and well-known agricultural characteristics that distinguish South Asia from most other large food-producing regions in the world govern this water demand. First, South Asia's agriculture is characterized by a high degree of multiple-cropping. A first crop during the monsoon season (Kharif) is often succeeded by a second crop during the dry season (Rabi) (Portmann et al., 2010). Planting dates for the Kharif crop are determined primarily by the onset of the monsoon rather than by an accumulation of degree days. High maximum temperatures form a constraint for crop production during the Rabi season, favouring planting as early as possible. Second, with rainfall highly concentrated during June till September and significant moisture deficits occurring during the other months of the year, crop production is to a very large extent supported by a combination of canal and groundwater irrigation, especially in the dry winter season (Rabi) (GoI, 2013).

Many models that are used for global to regional water resources assessments still lack representation of multiple-cropping (e.g.(Arnold and Fohrer, 2005; Best et al., 2011; Gerten et al., 2004; Liang et al., 1994)). Typically, a single cropping period per year is simulated with a degree-day based or predefined single planting date (see e.g. (Elliott et al., 2014; Kummu et al., 2014). Exceptions are the model by (Wada et al., 2011) who apply multiple-cropping in their estimation of water stress, but in a simplified aggregated form without distinguishing between different crops and the models of (Alcamo et al., 2003) and (Hanasaki et al., 2008) who apply multiple-cropping seasons using optimized planting dates. However, Hanasaki et al. (2008) note that their optimization mainly reacted to cold spells and was performed under rainfed conditions, which does not lead to optimal planting dates for the South Asia region. The study of Hoogeveen et al. (2015) accounts for multiple-cropping by incorporating national level FAO cropping calenders, but only present total mean annual irrigation demands for South-Asia (table 1). Siebert and Döll (2010) also take into account for multple-cropping by using MIRCA land use data (as the present study, see section 2.2) and cropping calenders. They show results for global seasonal irrigation demands, but not for South Asia specifically. As a result, crop-specific seasonal estimates of irrigation water demand in South Asia are still lacking.

In this paper, we aim to provide such spatially explicit, crop-specific seasonal estimates of water demand and crop production, using a revised version of the LPJmL hydrology and vegetation model (Gerten et al., 2004), adjusted for the region. We distinguish two main South Asian cropping periods, Kharif and Rabi, and introduce zone-specific, monsoon-onset-determined planting dates for 12 major crop types, both rainfed and irrigated. We calibrate the improved model against the latest sub-national statistics on seasonal crop yields from four different countries –India, Pakistan, Nepal and Bangladesh– and explicitly evaluate the irrigation water demand and crop production for the two cropping seasons.

2. Methodology

2.1. LPJmL

We used the LPJmL global hydrology and vegetation model for bio- and agro- spheres (Bondeau et al., 2007; Sitch et al., 2003), but developed a version that contains more spatial and temporal detail for South Asia. The LPJmL model has been widely applied to study the effects of climate change on water availability and requirements for food production at a global scale (Gerten et al., 2011); (Falkenmark et al., 2009) and the potential of rainfed water-management options for raising global crop yields (Rost et al., 2009). For South Asia, the model has been applied to study the adaptation potential of increased dam capacity and improved irrigation efficiency in light of climate change (Biemans et al., 2013). LPJmL physically links the terrestrial hydrological cycle to the carbon cycle, making it a suitable tool for studying the relationship between water availability and crop production. The model includes algorithms to account for human influences on the hydrological cycle, e.g. irrigation extractions and supply (Rost et al., 2008). Production and water use for 12 different crops, both rainfed and irrigated are simulated. LPJmL is a grid-based model, run at a resolution of 0.5 degrees, and at daily time step.

Net irrigation water demand (consumption) for irrigated crops is calculated daily in each grid cell as the minimum amount of additional water needed to fill the soil to field capacity and the amount needed to fulfil the atmospheric evaporative demand (Rost et al., 2008). Subsequently, the gross irrigation demand (withdrawal) accounts for application and conveyance losses, and is calculated by multiplying the net irrigation water demand with a country-specific efficiency factor (Rohwer et al., 2007), which is different for surface-water irrigation and groundwater irrigation (as in Biemans et al. (2013); Rost et al. (2008)). Irrigation efficiency for canal water ~~was~~is estimated at 37.5% in India, Bangladesh, Nepal and 30% in Pakistan (Rohwer et al., 2007); efficiency of groundwater irrigation ~~was~~is estimated at 70% for all countries (following Gupta and Deshpande, 2004b).

Surface water is defined as the water available in local rivers, lakes and reservoirs and is calculated by a daily routing algorithm (Biemans et al., 2009). Irrigation water demand is assumed to be withdrawn from available surface water first. If surface water is unavailable, it is assumed to be withdrawn from groundwater(Rost et al., 2008) .

Crop growth is simulated based on daily assimilation of carbon in 4 pools: leaves, stems, roots and harvestable storage organs. Carbon allocated to those pools depends on crop phenology and is adjusted in case of water stress on the plants. Crops are harvested when either maturity or the maximum number of growing days is reached (Bondeau et al., 2007; Fader et al., 2010).

To improve the understanding of spatial and temporal heterogeneity in irrigation water demand and crop production in South Asia, we made some adjustments to the version of LPJmL that is used for global studies. First of all, we introduced the simulation of two cropping cycles per year by developing two different land-use maps for Kharif and Rabi. Second, we applied zone-specific sowing dates related to monsoon patterns, and third, we accounted for regional differences in crop management by performing a calibration of crop yields at the subnational level. In the next three sections, those adjustments to LPJmL are explained in more detail.

In our experimental set-up, LPJmL is forced with daily precipitation, daily mean temperature, net longwave and downward shortwave radiation derived from the Watch Forcing Data applied to Era Interim data (WFDEI) (Weedon et al., 2014). Using this dataset, all LPJmL simulations were done for the period 1979-2009 after a 1,000 year spin-up period to bring carbon and water pools into equilibrium. The calibration and all analysis presented in this paper uses the simulation results of the period 2003-2008 for comparison with available statistics. Kharif and Rabi irrigation water demand and crop production are estimated by performing two simulations using different land-use input and sowing-date input datasets. Those two runs are subsequently combined to attain the seasonal pattern for irrigation water demand and crop production.

2.2. Development of land use maps for Kharif and Rabi seasons

To derive land-use input for two separate cropping seasons for South Asia, we used the MIRCA2000 database (MIRCA, version 1.1 (Portmann et al., 2010)) on a 5 minute resolution. MIRCA is a global spatially explicit data set on irrigated and rainfed monthly crop areas for 26 crop classes around the year 2000. On an annual basis, MIRCA is consistent with other gridded datasets for total cropland extent (Ramankutty et al., 2008), total harvested area (Monfreda et al., 2008), and area equipped for irrigation (Siebert et al., 2007), but has more temporal detail. For India, MIRCA2000 includes sub-national (i.e. state-level) information on the start and end of cropping periods. The dataset explicitly includes multiple-cropping.

Crop classes in MIRCA2000 were first aggregated to the crop classes available in the LPJmL model, which are fewer (12, irrigated and non-irrigated, plus one class with 'other perennial crops', versus 26 in MIRCA) but include the most important food crops for South Asia (see figure 2 for distinguished crops). The exact period of monsoon (Kharif) and dry season (Rabi) cropping differs according to region. In India, Kharif sowing is strongly related to the onset of the monsoon, whereas in large parts of Pakistan – where the monsoon is less pronounced – sowing can happen earlier or later because other factors like water availability for irrigation are more important. From the monthly MIRCA cropping calendars we decided to define the cropped area of the Kharif season as the area under cultivation per crop as in September and that of Rabi as the area per crop as in January. Perennial crops were only included in the Kharif land-use map.

Next, a few adjustments to the obtained data were made. First, MIRCA specifies three rotations of rice in northern India, two during summer and one during winter months. We merged the two summer rotations to the Kharif rice area and allocated one to the Rabi rice area, accepting a potential minor mismatch between datasets. Second, we corrected wheat and rice areas, both of which MIRCA equally divides over Rabi and Kharif. In reality, rice is mainly cropped during the Kharif season and wheat is only cropped during the Rabi (winter) season, when temperatures are lower and heat stress is avoided. We shifted all irrigated wheat to the Rabi season and made compensations where possible by shifting an equal amount of irrigated rice area to the Kharif season. Third, we shifted 45% of area cropped with pulses from the Rabi to Kharif season to comply with the latest agricultural statistics (GoI, 2012). In this way, consistency with other datasets was largely maintained (i.e. total cultivated area, cultivated area per crop, area irrigated), while at the same time a better match with crop phenology and regional agricultural practices was achieved.

Finally, we updated the area irrigated to the latest statistics. MIRCA represents land use and irrigated area for the period 1998-2002. Over the past 10 years, irrigated area has further increased in India alone from 76 million ha to 86 million ha (gross irrigated area), to 44% of the total area. Statistics for India show (GoI, 2012) that the increase in irrigated area occurred for all crops. By shifting 10% of rainfed area to irrigated area, while keeping the overall cropped area the same, we achieved an increase in gross irrigated area. We assumed that the all-India trend is mirrored in the neighbouring counties. Cropped area was then aggregated to 0.5 degree grids for both Kharif and Rabi, which formed the input into the LPJmL model. The resulting land use input is in good agreement with subnational statistics on cropping areas in Kharif and Rabi (see Annex A, Figure S1-S6).

Figure 1 shows the cropping intensity in the study region according to this newly compiled dataset, as well as the delineation of the river basins for which we will present our results. Figure 2 shows the total cropped area during the Kharif and Rabi seasons for all major crops in South Asia (India, Pakistan, Nepal and Bangladesh) according to the input data compiled here and compared to the agricultural statistics (GOI, 2014; Statistics, 2014).

2.3. Adjusted planting dates for Kharif and Rabi crops

Sowing dates for Kharif crops are closely related to the onset of the monsoon as farmers start (trans)planting rice or other crops when the first rains have arrived. Normal onset dates of the monsoon over South Asia are determined by the India Meteorological Department, at 5 to 15 day interval (IMD, 2015)(figure 3). The onset of the monsoon starts in Kerala in southern India around the first of June (Julian day 152) and arrives in western Pakistan around mid-July (Julian day 197). For the model simulations in this study, sowing dates for Kharif crops were set to five days after the onset of the monsoon, because several days of rain are needed before a crop is (trans)planted (figure 3). Inter-annual variations in the onset of the monsoon were not taken into account in this study. The perennial crop sugarcane is assumed to be planted on this date as well.

In general, the Kharif season ends by the end of October and the sowing of Rabi crops starts early – till mid-November until early January, depending on local temperatures during winter and water availability in spring. As the exact date is difficult to determine, we set the first of November as the single sowing date for the Rabi crops over the whole study area. Because the Rabi crops are generally harvested by the end of March, the irrigation water demand in the warm pre-monsoon summer months of April and May can almost entirely be attributed to perennial crops. In the analysis of seasonal irrigation demand, we therefore distinguish three seasons: Kharif, from June until October; Rabi, from November until March; and a 'summer' season from April to May.

2.4. Calibration of crop yields

Crop yields in LPJmL are calibrated by varying management intensity, which is represented by three parameters: maximum leaf-area index, maximum harvest index, and a parameter that scales leaf-level biomass production to plot level (Fader et al., 2010). The three parameters are related to crop density, crop varieties and the occurrence of poor soils, pests and diseases respectively (for a detailed description of the calibration procedure, see Fader et al., 2010) The value of these management factors affects the estimated water demand, because a poorly developed crop with little leaf area will evaporate less and therefore demands less (irrigation) water and vice versa.

The calibration is performed for each crop individually, and management factors are usually determined at the country level in global applications of LPJmL. For this model version, we calibrated crop yields for Kharif and Rabi separately, as they are differentiated in the agricultural statistics. Moreover, we calibrated the management parameters at the sub-national level for India and Pakistan (state- and province- level respectively) and at the national level for Nepal and Bangladesh. By calibrating at the sub-national level, existing spatial heterogeneity in management and crop yields between regions could be better represented. We used 5-year average yield statistics, for 2003-04 till 2007-08, the most recent period for which consistent records are available from different national agricultural statistics (India: GoI, 2012; Pakistan: http://www.pbs.gov.pk/content/agricultural-statistics-pakistan-2010-11, last visited 1-7-

2014; Bangladesh for the years from 2003-04 till 2005-06 form http://www.moa.gov.bd/statistics/statistics.htm#3 and for 2007-08 in the 2011 yearbook (http://www.bbs.gov.bd/PageWebMenuContent.aspx?MenuKey=234 ; Nepal:(GoN, 2012). After calibration, the model is able to simulate the heterogeneity of (mean annual) yields between states and regions (illustrated in ~~simulated crop yields matched well with observed yields in most regions (~~fig 4). Kharif rice and Kharif maize crops show the highest variation between states and provinces. Overall, yields during the Kharif season are lower than yields during the Rabi season, when a higher percentage of the area cropped is irrigated, and temperatures are more favorable. Interannual variations in crop yields are shown and discussed by Siderius et al (2016).

3. Results

3.1. Seasonality in agricultural water demand

Table 1 shows estimates of seasonal net (consumption) and gross (withdrawal from surface and groundwater) irrigation water demand between the four countries. India and Pakistan have the largest water demand, both in terms of consumption and withdrawal. While Pakistan's net irrigation demand is almost equally divided over the Kharif and Rabi seasons, India's demand is skewed towards the Rabi season; almost ¾ of net irrigation demand in India occurs in this dry season (including summer). This difference between Kharif and Rabi is less pronounced for gross irrigation demand, i.e. water withdrawals, which include application and conveyance losses. In the Rabi season a much higher proportion of the irrigation water is supplied from groundwater (table 1), which has a higher overall efficiency than surface-water irrigation from canals. ~~Irrigation efficiency for canal water was estimated at 37.5% in India, Bangladesh, Nepal and 30% in Pakistan (Rohwer et al., 2007); efficiency of groundwater irrigation was estimated at 70% for all countries (following Gupta and Deshpande, 2004b).~~

The seasonal distribution of irrigation water demand is a result of rainfall patterns in the region. In Bangladesh and Nepal, monsoon rainfall is abundant for sustaining crop production during the Kharif season and irrigation is therefore concentrated in the dry Rabi season. Groundwater irrigation, modelled as the resultant of demand minus surface-water availability, provides most water resources during the Rabi season in all countries, especially in India. In Pakistan, the Indus provides annually approximately 120 BCM of utilizable runoff, of which approximately 2/3 is used during the Kharif (Randhawa, 2002). Our estimate of mean annual groundwater withdrawal in Pakistan is at 60 BCM, of which ¾ occurs during the Rabi season and summer. This is somewhat higher than previous estimates of groundwater withdrawal, which were in the range of at 47 BCM to 55 BCM (Ahmed et al., 2007; Qureshi et al., 2003; Wada et al., 2010) but still lower than the estimated total potential of 68 BCM (Randhawa, 2002). For India, the exact distribution of surface-water and groundwater withdrawal between the Kharif and Rabi seasons is not well documented. Our model estimate of 217 BCM of groundwater withdrawal per year, mainly occurring during the Rabi season, is in agreement with earlier groundwater studies with estimates ranging from 190 (±37) BCM by (Wada et al., 2010) to 212.5 BCM (GoI, 2006).

Overall, our estimates of national total net and gross irrigation water demand are in line with earlier studies and statistics, but at the lower end of the range for India. Accounting for monsoon dependent planting dates, and thereby a more effective use of rainfall during the main Kharif cropping season, reduced our estimate of total agricultural water demand compared to earlier regional studies, e.g. with the LPJmL model (Biemans et al., 2013). For Pakistan, our estimates are on the high side compared to other studies. Especially for the Rabi season, we estimate a high additional demand from cash crops like cotton. This demand has to be met largely by groundwater abstractions, because runoff from the Indus and its tributaries is low during these months.

Evaluating the mean annual cycle of irrigation water demand per crop reveals the reason behind seasonal differences in demand (figure 5). The single peak in net water demand for wheat during the Rabi season stands out, while rice peaks in both Rabi and Kharif seasons. The moderating effect of monsoon rainfall during the Kharif season is obvious, with net irrigation water demand during the Kharif season only accounting for about 30% of the annual net irrigation water demand (table 1). So while water-use efficiency improvements in rice receive much attention, paddy fields being the epitome of excessive water consumption, rice is actually not the most water-demanding crop in the region. Because rice is grown mainly during the Kharif season in most states, its water demand is lower than for wheat and sugarcane, which are grown during the dry Rabi season. Those crops therefore depend much more on groundwater availability (see also table 1 and figure 6 for contribution of groundwater irrigation per cropping season). Additionally, sugarcane has an atypical demand in time, caused by its very long cultivation period of about 12 months; it requires large amounts of irrigation water in the hot dry months of March, April and May, a period when rainfall is scarce and most other fields are left fallow.

3.2. Seasonal patterns of water demand for different basins

As a result of varying climatological conditions and availability of spring and summer runoff from snow- and glacier- fed rivers, cropping patterns and thereby seasonal water demand pattern differ greatly between the major river basins (figures 6 & 7). The Indus basin shows a relatively stable irrigation water demand during the year, which is primarily fed by groundwater in winter and melt runoff in summer (figure 7). Downstream, monsoon rainfall contributes little to crop water needs. In the Ganges basin, a more seasonal pattern can be seen with demand for irrigation water being lower during the monsoon, when rainfall is sufficient over large parts of the basin, and no additional irrigation is needed. The same pattern can be seen to be even stronger in the Brahmaputra basin.

3.3. Food production in South Asia during the Kharif- and Rabi- cropping seasons

Figure 8 shows the total seasonal production of only the five most important food crops (wheat, rice, maize, tropical cereals and pulses), both for the region as a whole as for the individual basins. The total area irrigated to grow these food crops is smaller in Kharif than Rabi (35 Mha vs 46 Mha total for the four counties), but total (rainfed plus irrigated) area used to grow these food crops is much larger in Kharif than Rabi (95 Mha vs 57 Mha). While the percentage of area under irrigation, productivity per hectare and sources of water used greatly differ between the Kharif and Rabi seasons, total regional food-crop production is remarkably similar in the two seasons. A lower cropped area during the Rabi season is compensated for by higher yields. Of the total production of food crops in South Asia during the Kharif season, ~50% is supported by irrigation (figure 8). In the Rabi season up to ~95% of food-crop production is supported by irrigation. These estimates agree with the recent study of Smilovic et al. (2015) who focus on rice (kharif and rabi) and wheat (rabi) production in India only. They show that during kharif 68% of rice production is produced on irrigated lands, which is only 56% of the rice area sown. During rabi this percentage is much higher: 96% of the rice was irrigated (on 89% of the sown area) and 97% of the wheat production was irrigated (on 93% of the sown area) (Smilovic et al., 2015).

We also calculated the potential rainfed yield on those areas currently irrigated. Absence of irrigation would reduce the Kharif food-crop production with ~15% (dark blue bar in figure 8), against a reduction of almost 60% in Rabi. This stresses the importance of sufficient irrigation- water supply for achieving food security in this region.

A closer look into the seasonal food production in the different river basins shows clear differences. The Indus and the Ganges have a much higher annual production of food crops than the Brahmaputra.

Rabi is the most important season for the production of food crops in the Indus. The same is true for the Ganges, although the production levels between the seasons are closer to each other. The rainfed production is much larger in the Ganges than in the Indus. In the Brahmputra basin, the majority of food-crop production takes place during the Kharif season.

4. Discussion

The seasonal estimates presented here on food production and related irrigation water demand in South Asia form a new baseline estimate of South Asian seasonal-water demand and food-crop production, as they provide more spatial, temporal and crop-specific details than previous estimates.

Incorporating seasonal cropping patterns in more detail leads to improved estimation of the timing of water demand. Figure 5 shows that the simulated timing of water demand is very different compared to a simulation with old settings – thus single cropping season and calculated sowing dates. We show that seasonal water demand is a factor of crop-specific seasonal consumption, availability of rainfall and different sources of water supply, i.e. groundwater or surface water, and the irrigation efficiencies connected to these sources. Despite these improvements, when modelling such large basins with complex hydrology and high diversity in agricultural and water-management practices, inevitably simplifications and local inaccuracies remain.

Our estimate of the net irrigation requirement (consumption) is influenced by the performed calibration and resulting management factors. Generally, regions with high management factors will show higher yields and higher transpiration, but lower soil evaporation. The effect of the calibration on our estimate of net irrigation requirements was tested by making two model runs: one with all management parameters set to the lowest possible value and one with all management parameters set to the highest possible values. This resulted in a net irrigation requirement for South Asia between 307 and 389 km^3, a variation of about 10% compared to the here reported mean annual value of 346 km^3.

Our estimate of gross irrigation demand, the water withdrawal, is strongly influenced by the water use efficiency value used, which is determined by a variety of factors like local irrigation practices, scale of analysis and source of water use. We used the most commonly reported values for the region, similar to other model-based studies in order to be able to compare results. Inclusion of regional, more application- and water-source-specific water use efficiency values in models would improve the estimation of gross water demand. Such detail is also necessary to gain better insight into the adaptation potential of different measures like drip irrigation and alternate wetting and drying.

More attention to seasonal cropping patterns and their water demand opens the scope for further model improvement. Double-cropping was evaluated by combining two seasonal model runs, one for Kharif and one for Rabi. Use of residual soil moisture from one season to the other was not incorporated in this way, nor could the continued depletion of groundwater be accurately modelled. An integrated double-cropping routine, with proper calibrated crop-specific planting dates and yields, would provide such necessary analysis in a region where groundwater depletion is of serious concern.

Next, estimation of planting dates should be further improved, using detailed information on local agricultural practices and local water availability. Further, the sowing dates were kept constant during the whole simulation period and was based on average data of monsoon onset, although actual onsets vary year by year. In reality a farmer might decide year to year to sow earlier or later which introduces an incertainty in our calculations. Ample information is available in the irrigation domain but it will require a form of cooperation between experts at the local to national level and the water resources modelling community. Sharing of input data might reduce costs and time expenditure, will increase its uptake and improve overall quality of water resources assessments.

Finally, cropped area and sources of irrigation used are not constants or slowly evolving properties, but can be highly variable on inter-annual time scales in response to climate variability (Siderius et al., 2013b). These fluctuations were not assessed in the current study but are of high importance to individual farmers and the overall profitability of agriculture in regions with a variable climate. Combining an improved baseline of seasonal water demand with the inter-annual fluctuations in cropped area will lead to a more realistic assessment of both water demand and crop production, of high relevance in today's world with its volatile food commodity markets.

This paper highlights crop-specific periods of peak water demand that can form critical moments in agricultural production. Such better understanding of the size of water demand during critical moments, the crops that are responsible for this water demand, and its relative importance for food production is essential to guide sustainable development of climate adaptation measures. This analysis can support the selection of promising options to decrease irrigation water demand. When combined with information on the (un)availability of surface water and the resulting pressure on groundwater resources (figure 7), it improves our understanding on the causes of water shortages and groundwater depletion. Finally, insight in the yield gap between rainfed and irrigated agriculture in specific regions, and between regions, can help target investments to improve irrigation practices or to increase productivity of rainfed agriculture.

5. Conclusions

Introducing seasonal crop rotation with monsoon-dependent planting dates in a global vegetation-hydrological model leads to better seasonal estimates of irrigation water demand. Irrigation water demand between the two main cropping seasons differs sharply both in terms of source and magnitude; gross irrigation demand during the Rabi season is ~30% higher~~lower~~ than during the Kharif season, the traditional cropping season, when monsoon rainfall reduces the amount of supplemental irrigation water needed. Our estimate of total annual water demand is lower than that of previous studies (Biemans et al, 2013), despite the net irrigated area being higher. Overall, gross annual irrigation demand is estimated at 714 BCM; 247 BCM during the Kharif monsoon season, 361 BCM during Rabi and 106 BCM during the summer months of April and May.

Seasonal estimates of agricultural water demand better highlight crop-specific differences in peak water demand. Such increased temporal detail is needed for properly evaluating the impact of expected shifts in supply of water as a result of a rapidly changing climate, especially in the Himalayan headwaters of some of the main rivers in South Asia. With temperatures rising and total precipitation fairly constant, increased melt from glaciers combined with an early melt of the snow cover is expected to shift the peak in spring runoff to early in the season (Immerzeel et al., 2010; Lutz et al., 2014). Whether this shift will affect critical moments for irrigation or the ecosystem as a whole is to be assessed.

Our study has thereby more than regional relevance. Given the size and importance of South Asia, in terms of population and food production, improved regional estimates of production and its water demand will also affect global estimates. In models used for global water resources and food-security assessments, processes like multiple-cropping and monsoon-dependent planting dates should not be ignored.

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Table 1. Seasonal and total net and gross irrigation water demand estimates (BCM) and groundwater contribution to irrigation-water supply for individual countries and South Asia as a whole (India, Pakistan, Nepal and Bangladesh).

	net irrigation demand (consumption)				Other estimat	percentage groundwater irrigation				gross irrigation demand (withdrawal)				Other estimates
	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Total	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Total
Nepal	0.1	1.0	0.2	1.4		19%	62%	34%	54%	0.3	2.0	0.5	2.7	10[e]
Pakistan	38	42	16	96	117[d]	25%	68%	25%	44%	110	86	47	243	200.2[h], 162.7[b], 117–120[c], 187.8[g]
India	59	148	31	235	317[d]	27%	79%	63%	64%	136	249	58	443	575.9[h], 541[a], 558.4[b], 710–715[c]
Bangladesh	0.1	11	0.3	12		10%	43%	2%	41%	0.2	24	0.8	25	31[e]
South Asia	97	202	48	346		26%	74%	50%	58%	247	361	106	714	985 [f]

	net irrigation demand (consumption)				Other estimat	percentage groundwater irrigation				Other estimat	gross irrigation demand (withdrawal)				Other estimates
	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Total	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Total	Kharif (M6-10)	Rabi (M11-3)	Summer (M4-5)	Total	Total
Nepal	0.1	10	0.2	14	4.4[d]	19%	62%	34%	54%	20%[d]	0.3	2.0	0.5	2.7	10[e]
Pakistan	38	42	16	96	117[d]	25%	68%	25%	44%	33%[d]	110	86	47	243	200.2[h], 162.7[b], 117–120[c], 187.8[g]
India	59	148	31	235	317[d]	27%	79%	63%	64%	64%[d]	136	249	58	443	575.9[h], 541[a], 558.4[b], 710–715[c]
Bangladesh	0.1	11	0.3	12	24[d]	10%	43%	2%	41%	76%[d]	0.2	24	0.8	25	31[e]
South Asia	97	202	48	346	480[i], 532[j]	26%	74%	50%	58%		247	361	106	714	985 [f], 910[j]

a GOI (2005). Water Data Complete Book, Central Water Commission, Ministry of Water Resources, Government of India.
b AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm).
c Rost et al. (2008).
d Siebert et al. (2010).
e AQUASTAT with reference to 2008 for Bangladesh and 2005 for Nepal. Approximately 79 percent of the total water withdrawal comes from groundwater (Nepal) and 21 percent (Bangladesh)
f Rosegrant and Cai (2002). 1995 estimate using a basin efficiency of 0.54.
g Water Resources Section, Ministry of Planning and Development in (Ahmed et al., 2007).
h Biemans et al. (2013)
i Siebert and Döll (2010)
jHoogeveen et al. (2015)

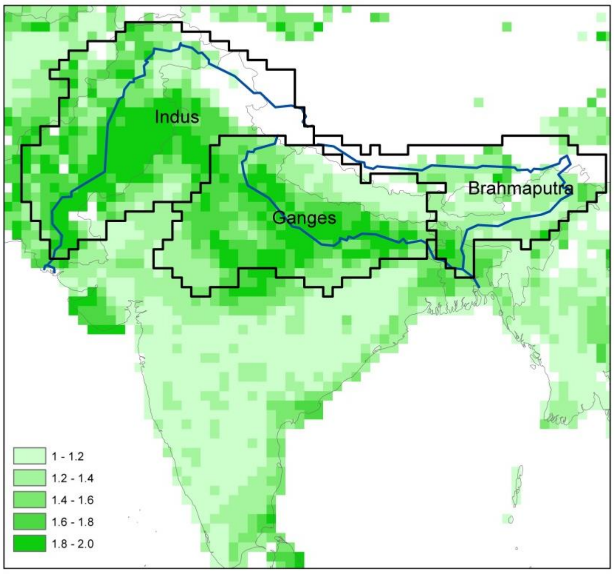


Figure 1. Cropping intensity in South Asia (land use datasets derived for this study based on MIRCA2000. Average cropping intensity is defined here as the total annual harvested area (Kharif and Rabi) divided by the maximum cropped area of the two cropping seasons. Study-basin delineations are indicated in black.

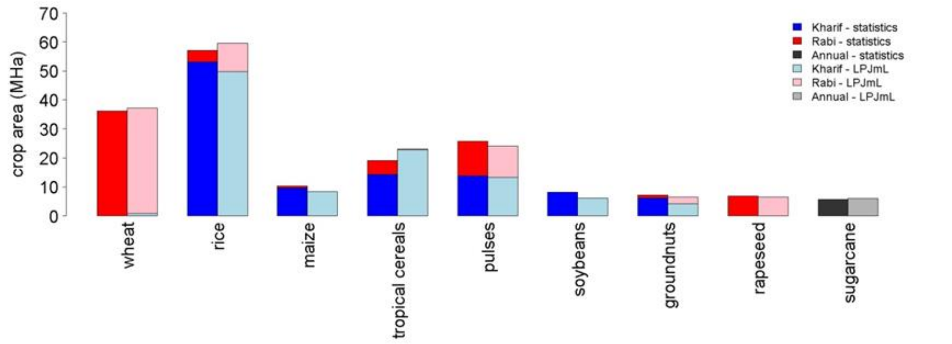


Figure 2. Total crop area in South Asia (India, Pakistan, Nepal and Bangladesh) for different crops in the two dominant growing seasons. National statistics (average of 2003-2008) versus LPJmL input data derived from MIRCA as described in section 2.2. For the spatial distribution of crops between states and provinces of India and Pakistan, Nepal and Bangladesh, see Annex. Temperate and tropical roots and sunflower are not shown because they occupy relatively small areas; other perennial crops are not shown because there are no statistics available.

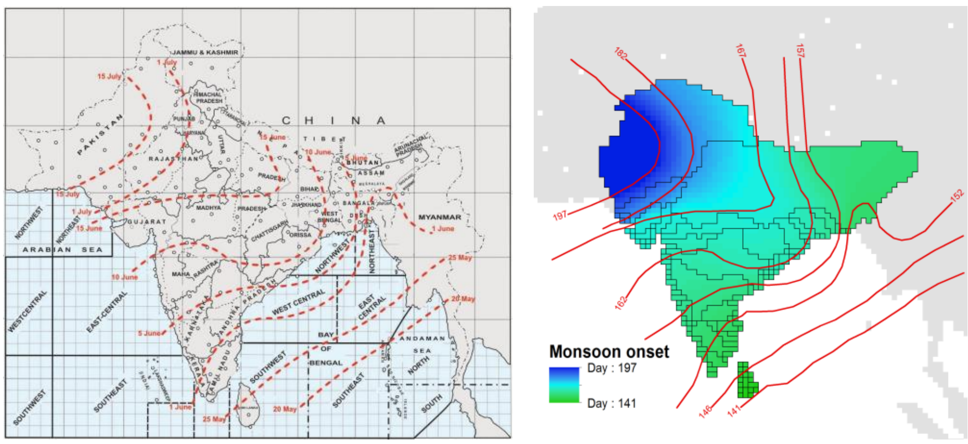


Figure 3. Normal dates for the onset of the Southwest Monsoon as presented by the Indian Meteorological Department (left) and interpolated over South Asia (right) derive input data for LPJmL, red numbers indicating Julian days, grey lines showing basin boundaries.

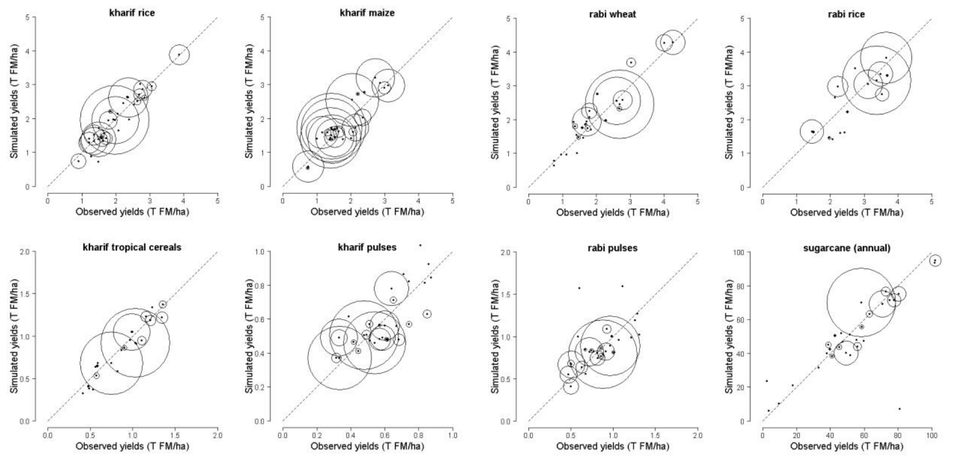
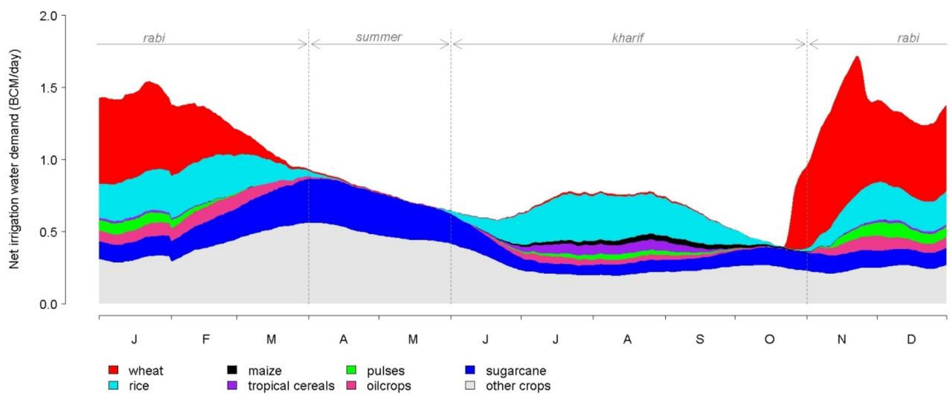


Figure 4. Observed vs simulated (calibrated) crop yields for the most important crops in the different cropping seasons. Each dot represents one state (India), province (Pakistan) or country (Nepal, Bangladesh). Size of the circle represents the relative area under that crop (for areas, see figures S1-S6 in the Annex).



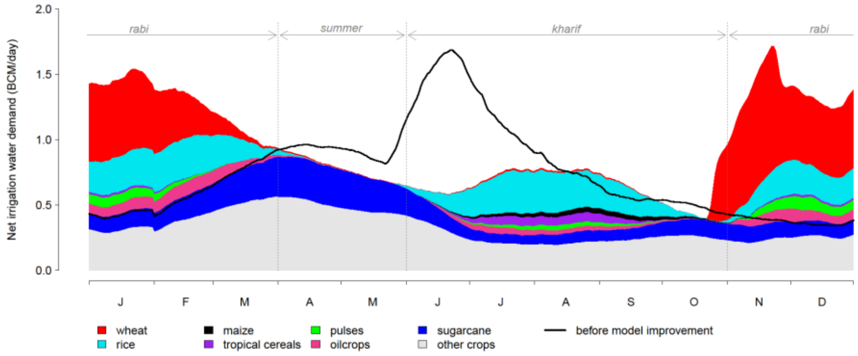


Fig 5. Mean annual cycle of net irrigation requirements for main agricultural crops in South Asia (30-day moving average). For comparison, the mean annual cycle of net irrigation requirements before model improvements (with single cropping season and climate driven sowing dates determination) is added in black.

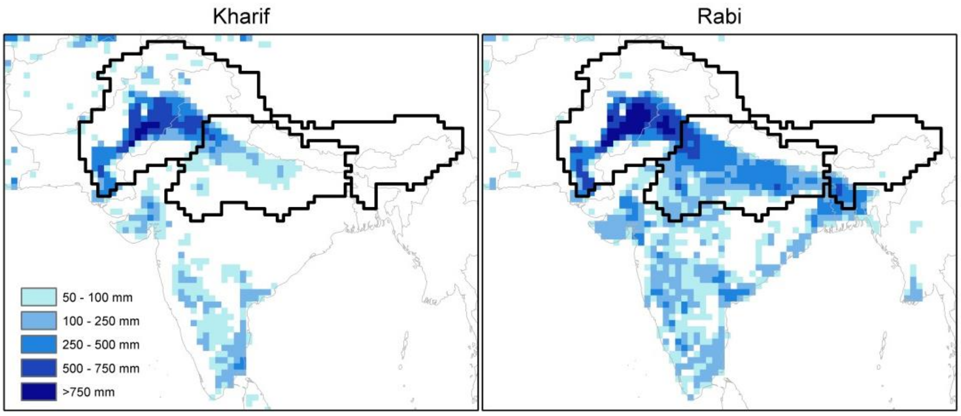


Fig 6. Gross irrigation water demand for Kharif (M6-10) and Rabi (M11-3) cropping seasons, with selected river basins (Indus, Ganges, Brahmaputra).

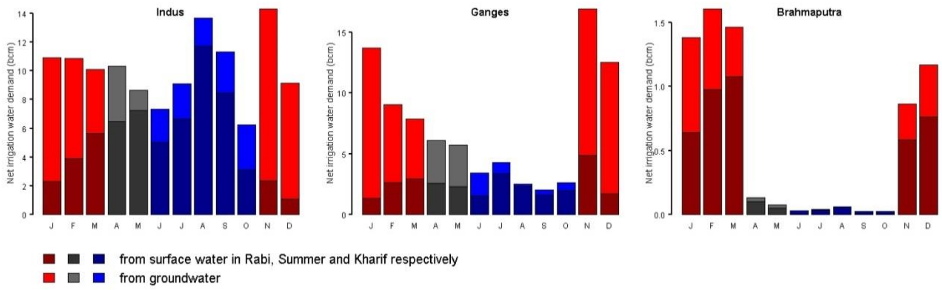


Figure 7. Monthly net irrigation water demand for three river basins. Colours indicate the different seasons (red – Kharif, grey – summer, blue – Rabi) and the dark areas the source for supplying the irrigation water (dark – surface water, light – groundwater).

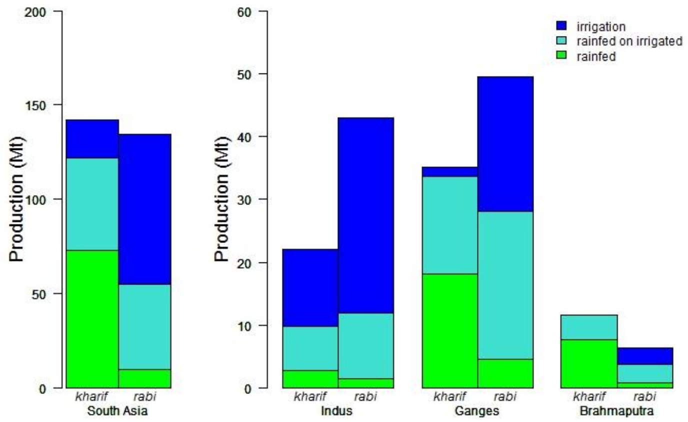


Figure 8. Seasonal irrigated (blue) and rainfed (green) production of food crops (sum of wheat, rice, maize, tropical cereals and pulses) in South Asia (Nepal, Pakistan, India and Bangladesh) and individual river basins. Light blue corresponds to potential rainfed production on irrigated land, i.e. dark blue corresponds to the increase in production due to irrigation.