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The limits of increasing food production with irrigation in India

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Abstract Growing populations and dietary shifts to include higher proportions of meat are projected to double global food demand by 2050. Previous global studies have proposed and evaluated possible solutions by closing agricultural yield gaps, defined as the difference between current and potential crop yields. We compliment previous studies by developing a method for more accurately calculating potential changes in cereal grain production under different irrigation scenarios, explicitly incorporating yield differences associated with different sources of irrigation. Irrigating with groundwater often leads to higher crop yields than irrigating with surface water because of the greater facility to tailor both the volumes of water and the timing of application. Two possible scenarios for increasing production in India are examined, the first where all non-irrigated fields are irrigated proportionally to the State-specific distribution of irrigation sources, and the second where all non-irrigated fields are irrigated with groundwater: Rice production increases by 14 and 25 % in scenarios 1 and 2 respectively, but wheat production increases by only 3 % in both scenarios. Increased irrigation water consumption from irrigating fields that are currently non-irrigated is estimated at 31 % for rice and 3 % for wheat using the Global Crop Water Model. A third scenario estimates the potential loss in production without the use of irrigation: rice would be 75 % and wheat 51 % of current production. Our methodology and results can help policy makers estimate the current and potential contribution of irrigation sources to agricultural production and food security in India and can with facility be applied elsewhere.

Keywords Irrigation · Agriculture · India · Wheat · Rice · Food security

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Introduction

The global population of seven billion is estimated to increase to over nine billion in the next few decades (United Nations 2013), which will likely impact both food security and the environment (Tilman et al. 2002; de Fraiture et al. 2007; Godfray et al. 2010; Food and Agriculture Organization of the United Nations 2009; Foley et al. 2011). Agriculture is now arguably the greatest human activity potentially straining the limits of planet earth's resilience and humanity's support system (Rockström et al. 2009), with agriculture the largest user of water (Lundqvist et al. 2008). Irrigation helps meet crop water requirements and improves crop yields at the expense of diverting and depleting surface and groundwater systems. Recent research has demonstrated that closing the yield gap for rice and wheat production would produce approximately 40 % more rice and 60 % more wheat globally (Licker et al. 2010). The *Yield Gap* is the difference between current yields and potential yield, and calculations are therefore subject to different estimates of potential yield. Previous global studies on yield gaps and potential production distinguish only between crop type and climatic zone and do not acknowledge potential limiting factors influenced by the distinct agricultural and socioeconomic differences among nations and sub-nations (Licker et al. 2010). To incorporate such potential limiting factors, we determined unique *crop- and* *season-specific* potential yields for each of India's political jurisdictions (States and Union Territories).

Worldwide, between ~20 and 30 % of agricultural land is irrigated (de Fraiture et al. 2007; Molden et al. 2007), with surface water irrigating ~60 % and groundwater irrigating ~40 % of the net area irrigated (Siebert et al. 2010). Previous research suggests that irrigated land needs to be expanded in order to meet the demands of growing populations and dietary shifts against a background of increasing climatic variability (World Bank 2010b). Recent trends in agricultural practices suggest that this expansion will be based on the intensification of groundwater irrigation, particularly in the developing world (Shah et al. 2007). Groundwater often leads to higher crop yields and is more water productive than surface water because of the greater facility to tailor both the volumes of water and the timing of application (Dhawan 1995; Hernandez-Mora et al. 2001; Llamas and Custodio 2003; Shah et al. 2003; Siebert and Döll 2010). However, intensive use of groundwater can adversely affect aquifers, including but not limited to aspects such as water quality, water quantity, land elevation, discharge, and surrounding ecosystem services (Custodio and Llamas 2003; Gleeson et al. 2012). Groundwater depletion, mainly due to irrigated agriculture, is of particular severity and concern in the semi-arid and arid regions of Pakistan, India, China, the United States of America, Iran, Yemen, and Spain (Wada et al. 2010, 2012; Konikow 2011). Previously no method has been developed to evaluate region-specific current and potential increases in yields parsed by irrigation source.

We focus on India as food security in this country is directly linked to complex and rapidly evolving irrigation practices which cause both groundwater depletion and surface water stress; 44 % of cultivated land in India is irrigated (Fig. 1) (Vörösmarty et al. 2000; Gleeson and Wada 2013; Rodell et al. 2009; Tiwari et al. 2009; Kumar et al. 2012). Indian farmers are transitioning away from traditional sources of irrigation, largely reflective of the declining reliance on centralized surface reservoir and canal schemes, and the rise of the independent farmer which has been called the "era of atomistic irrigation" (Shah 2009). India continues to invest funds (US $20 billion since 1990) in repairing, rehabilitating, and building surface structures (Shah 2009), while canal irrigation has declined (13.8 % between 1996 and 2003) (Janakarajan and Moench 2006). The expansion of agricultural land has also been largely without the usual canal and reservoir irrigation supply schemes: 84 % of the net area irrigated added in the past 20 years is irrigated with groundwater (Gandhi and Bhamoriya 2011). Groundwater irrigates 65 % of the gross area irrigated (Fig. 2) and farmers now collectively abstract from ~20 million bore wells (Briscoe and Malik 2006; Central Ground Water Board 2011). Centralized national and State governments are now trying to manage the issue of declining groundwater tables, the development of which was decentralized and localized (World Bank 2010a; Central Ground Water Board 2011).

We present two possible future scenarios for irrigation in India for estimating potential increases in production, and a third scenario in which currently irrigated lands sown with rice or wheat are grown under non-irrigated conditions. We accompany the expansion of irrigation with estimates of the increases in irrigation water consumption. The first scenario is consistent with the continued investment of funds in public infrastructure (Shah 2009) and assumes that any serious efforts to expand irrigation would be, in part, by increasing public supply schemes in the form of canals and surface structures. In this scenario each State adopts irrigation schemes on all non-irrigated lands proportionally to the State's current use of irrigation sources. In the second scenario, we assume that the expansion of irrigation to include all currently non-irrigated lands sown with rice or wheat is achieved solely through groundwater development, and any investment in public supply surface structure would work to rehabilitate and repair currently employed surface water schemes instead of building new infrastructure. This scenario is motivated by the documented trend that Indian farmers are shifting away from traditional canal and reservoir irrigation supply schemes towards groundwater irrigation (Shah 2009; Janakarajan and Moench 2006). In a third scenario, we estimate the potential loss in rice and wheat grain production in India caused by withholding irrigation. The third scenario is not motivated by trends in India's agricultural development, but calculated to complement the two previous scenarios. Our methods implicitly acknowledge the increases in yields due to seed varieties, inputs, and management styles currently available and adopted within each State per crop and irrigation source.

Our objective is to quantify the increase in marketable production of rice and wheat grains in India by closing yield gaps by irrigating currently non-irrigated fields, acknowledging that this will lead to additional depletion of water resources. We provide a reference for national- and State-level governments to recognize regions for potential increases in rice and wheat grain production presented with the necessary associated increases in area equipped for irrigation and irrigation water consumption. Further, we provide a framework for both governmental and non-governmental agencies, policy makers, and water managers to evaluate the role of surface water and groundwater in India's food production by attributing to each irrigation source its current contribution to rice and wheat grain production. The novel methods developed in this paper can be extended to other nations and sub-national jurisdictions, as well as to different crops. The results help quantify the relationship between irrigation source and crop production, and further articulate a much-needed understanding of the tradeoffs between water resources and food production.

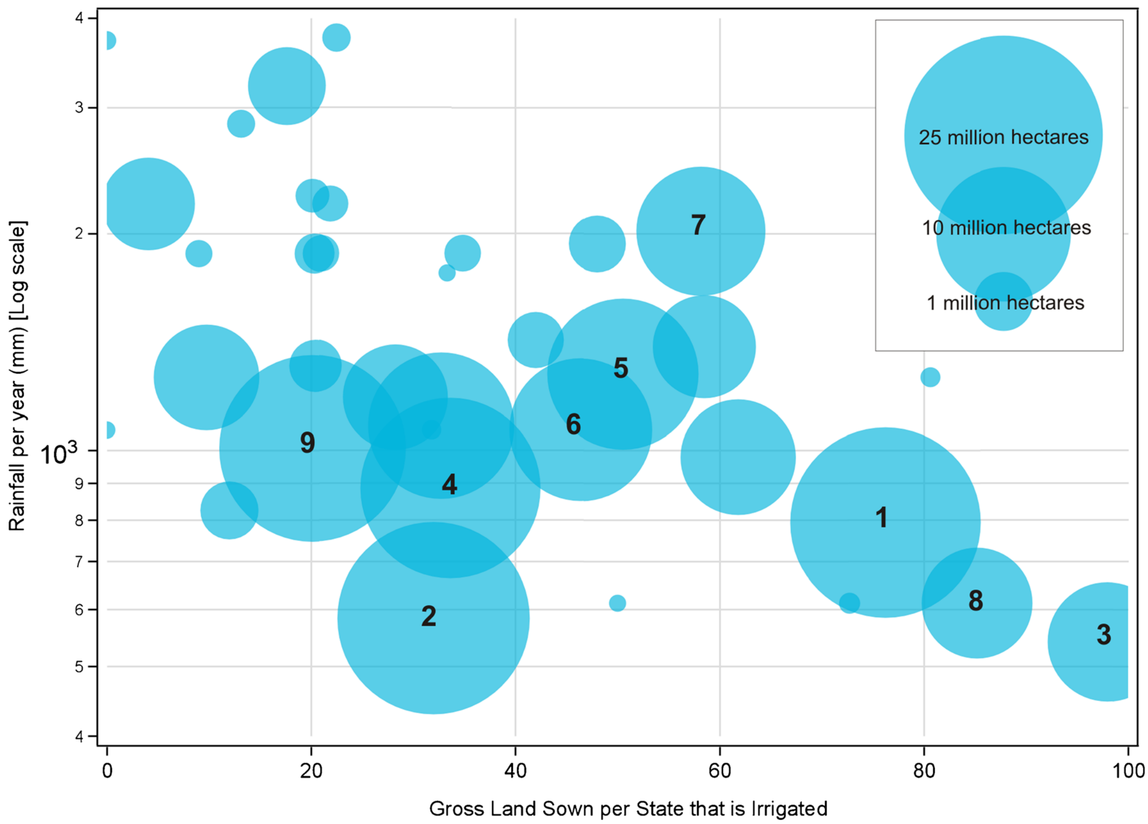


Fig. 1 Rainfall and land sown per State. Each *circle* represents a State, and the *size of a circle* represents the gross area sown in that State. A power function with an exponent of 0.4 is used to relate gross area sown to circle area to facilitate visualization. The *numbers on the circles* are representative of States as follows: *1*. Uttar Pradesh, *2*. Rajasthan, *3*. Punjab, *4*. Madhya Pradesh, *5*. Andhra Pradesh, *6*. Gujarat, *7*. West Bengal, *8*. Haryana, *9*. Maharashtra (see map in Fig. 2)

Global analysis of irrigation and agriculture: limitations and definitions

The partitioning of irrigated land into its various sources has been approached previously at a global scale (Burke 2002; Shah et al. 2007; Giordano 2006; Thenkabail et al. 2009; Siebert et al. 2013). Most recently, Siebert et al. (2013) have provided estimates based on information available for *area equipped for irrigation* and *net area irrigated* for 36,090 national and subnational administrative units. We have updated and expanded these previous efforts by employing national and State-level databases and statistics to improve such estimates for India.

Potential Yield is defined by Licker et al. (2010) as the maximum yield achieved worldwide per crop and climate zone. *Yield Gap* is the difference between current yields and potential yield. This calculates the maximum yield of crops possible under currently available and globally somewhere-adopted management practices and seed varieties. However, assuming this as the potential maximum on all fields of the same crop type (regardless of variety) and in a similar climate assumes a world with homogenous economic, social, and political conditions, as well as a world with homogenous agricultural and management practices. Instead, our method calculates this maximum yield specific to State, season, and crop. This establishes potential yields per political jurisdiction and allows us to estimate crop production potentials which are consistent with each State's current production and irrigation schemes, current access to seed varieties and technologies, management practices, and social environment.

The loss of production from stopping irrigation has previously been estimated by Siebert and Döll (2010). They used the MIRCA2000 (Portmann et al. 2010) dataset for land classification (crop-type and irrigated or non-irrigated) and total crop yields from Monfreda et al. (2008). Without a global data set disaggregating total crop yields into irrigated and non-irrigated yields, the difference was estimated as being related to the difference between potential crop evapotranspiration and actual crop evapotranspiration, combined in *crop- and climate-specific* relationships. Concessions were made to accommodate a global analysis and the coefficients and yield parameters associated with each crop were aggregate estimates over all crop varieties and made mainly from data available from the USA (Siebert and Döll 2010). Our method

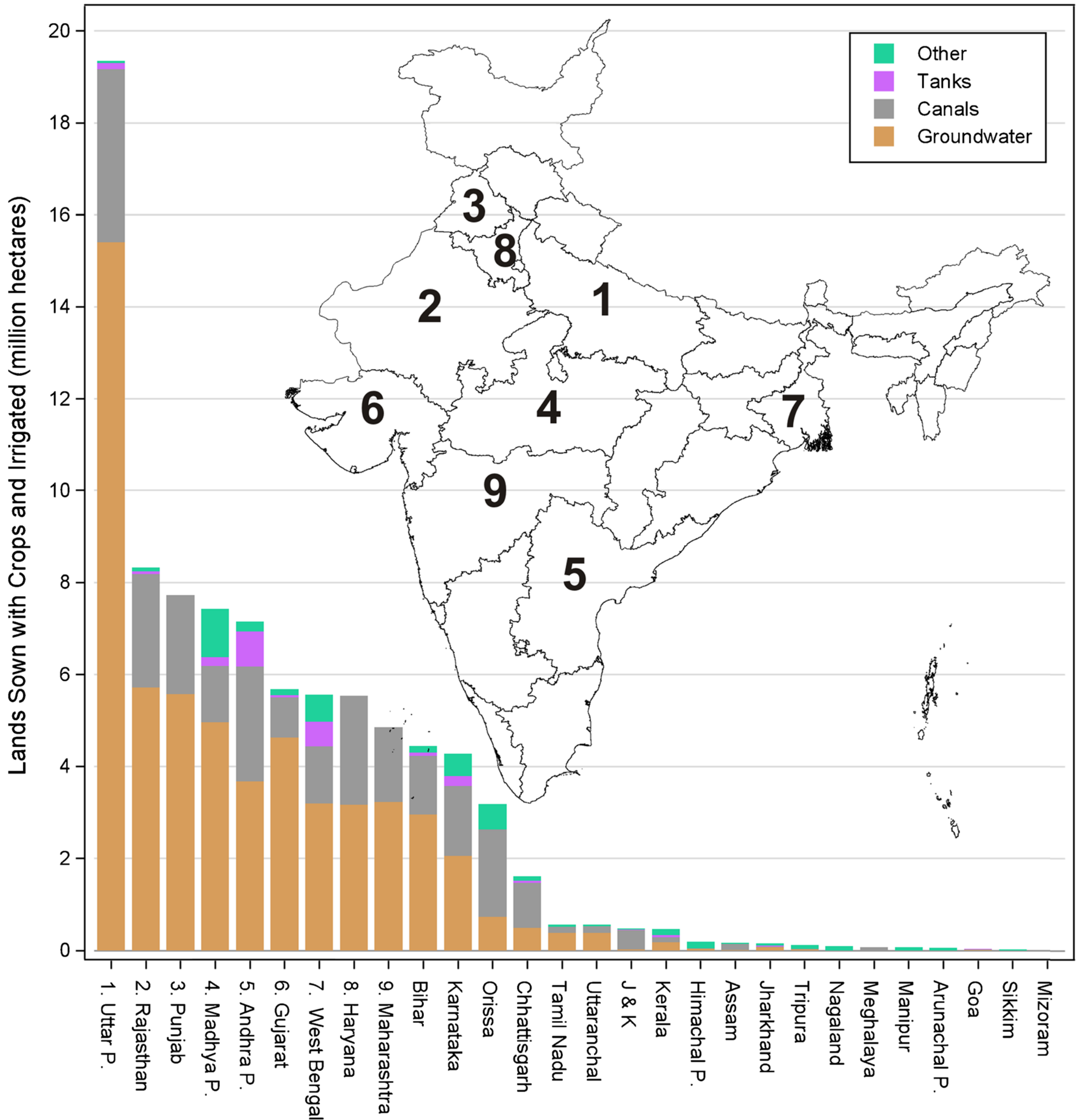


Fig. 2 Types and extent of irrigation in India by State. The total height of each *bar* is the total area irrigated in the associated State. Individual components of each *stacked bar* represent the contribution of each irrigation source to the total

explicitly considers the yield differences between irrigated and non-irrigated fields, and the specific sources of irrigation in the former.

Irrigation and agriculture in India

The green revolution of the 1960s in India improved marketable yields of crops and provided a significant increase in production with the introduction of high-yielding varieties, chemical fertilizers, and irrigation technologies (Gandhi and Bhamoriya 2011; Llamas and Custodio 2003). The green revolution is also associated with the loss of crop diversity, increased pesticide use, declining soil health even with the advent of increasing fertilizer application, water depletion and shortages associated with the high water requirement of high-yielding crop varieties, and farmer dependency on seed technologies (Shiva 1991; Seckler 1998). Farmers are shifting from being dependent on traditional and costly supply-driven canal schemes to self-managing their irrigation practices and water supply. India is now the world's largest user of groundwater, driven largely by agriculture (World 2010a; Shah et al. 2007; Garduño et al. 2011) and is a hotspot of groundwater depletion (Mall et al. 2006; Rodell et al. 2009; Wada et al. 2010, 2012; Gleeson et al. 2012). India's food security is directly linked to groundwater: 49 % of India's rice production and 72 % of wheat production are irrigated with groundwater. Several factors have been instrumental in the rapid development of groundwater resources: increasing agricultural and urban demands on water, unreliable or insufficient public water supply systems, the reliability and local availability of groundwater resources, the introduction of relatively inexpensive pump technologies, and government subsidized electricity in many regions (Shah 2009). India uses less than 61 % of its net annual available groundwater, defined as the annual replenishable groundwater resources minus an estimated allocation for natural discharge (Central Ground Water Board 2011). However, water use is not necessarily correlated with water availability and most water use is centralized in the most populated and economically productive areas: 30 % of aquifers are categorized as in critical condition, with an estimated growth to 60 % in the next 20 years under current conditions (World 2010a; Gleeson and Wada 2013).

India currently sows 43 million hectares of rice and 30 million hectares of wheat, 22 and 15 % of gross sown agricultural land respectively (Fig. 3). The percentage of land irrigated for each of these two crops is significantly different from the aggregate average of 44 %: 93 % of lands sown with wheat and 60 % of lands sown with rice are irrigated; only 28 % of other crops are irrigated (Fig. 3). India currently produces 96 million tonnes and 87 million tonnes of marketable rice and wheat grain respectively (Fig. 4).

There are generally two growing seasons in India: the Kharif from May to September, and the Rabi from October to April. The Kharif is characterized generally as the Wet season with 79 % of the annual precipitation (representative of the growing season of 2010–11), and the Rabi as the Dry season, and we will refer to them as such. Rice is grown mainly in the wet season with only 16 % of rice production grown in the dry season (representative of the growing season of 2010–11), and wheat is grown solely in the dry season. We use “State” to refer to any of the 28 Indian States or 7 Union Territories.

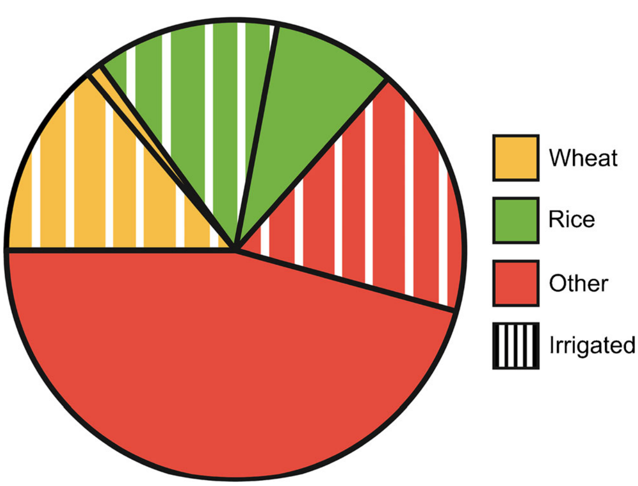


Fig. 3 The distribution of gross area sown in India with rice, wheat, and other, and the proportion of each under irrigation

Methods

The potential increase in rice and wheat grain production in India was calculated by closing yield gaps while neither expanding agricultural land, nor changing the crop-type of currently sown land. First, the gross area sown was calculated for each crop in each State, each season, and for each irrigation source: groundwater, canals, tanks (relatively small surface water reservoirs), and other (designated as surface water). Second, *State-, season-, and crop-specific* yield differences were calculated between irrigated and non-irrigated fields sown with rice or wheat, and further between irrigation sources. We could then partition *State-, season-, and crop-specific* rice and wheat grain production into the production resulting from irrigated and non-irrigated fields, and similarly the production from irrigated fields into the production resulting from the various irrigation sources. Finally, we calculated *State-, season-, and crop-specific* changes in rice and wheat grain production under three different irrigation scenarios. Among the estimates, we provide a range of agricultural production as it relates to irrigation and the production with maximum consumptive irrigation water use to the production with zero irrigation water use.

Data were derived from censuses and statistical surveys and reports made available by the Government of India and the Directorate of Economics and Statistics of State governments, the Directorate of Economics and Statistics of the Department of Agriculture and Cooperation, Ministry of Agriculture, the Indian Meteorological Department, and the Central Ground Water Board and Central Water Commission, both of the Ministry of Water Resources. Table 1 attributes to each variable its origin, either from data (including manipulations of data) or derived (calculations or estimates from equations and generally with assumptions). Variables are generally *State-, season-, and crop- specific*, and exceptions are noted otherwise. The data on rainfall, area sown, irrigation, irrigation source distribution, and production reflect the 2010–11 growing year, namely May 1, 2010- April 30, 2011.

Area

We calculated the *State-, season-, and crop-specific* area sown with rice or wheat and irrigated with groundwater, canals, tanks, or other. We assumed a particular crop irrigated in a particular State in a particular season was irrigated proportionally to the use of irrigation sources in that particular State:

$$A_{Source} = A_I \cdot \frac{A^*_{Source}}{A^*_I} \quad (1)$$

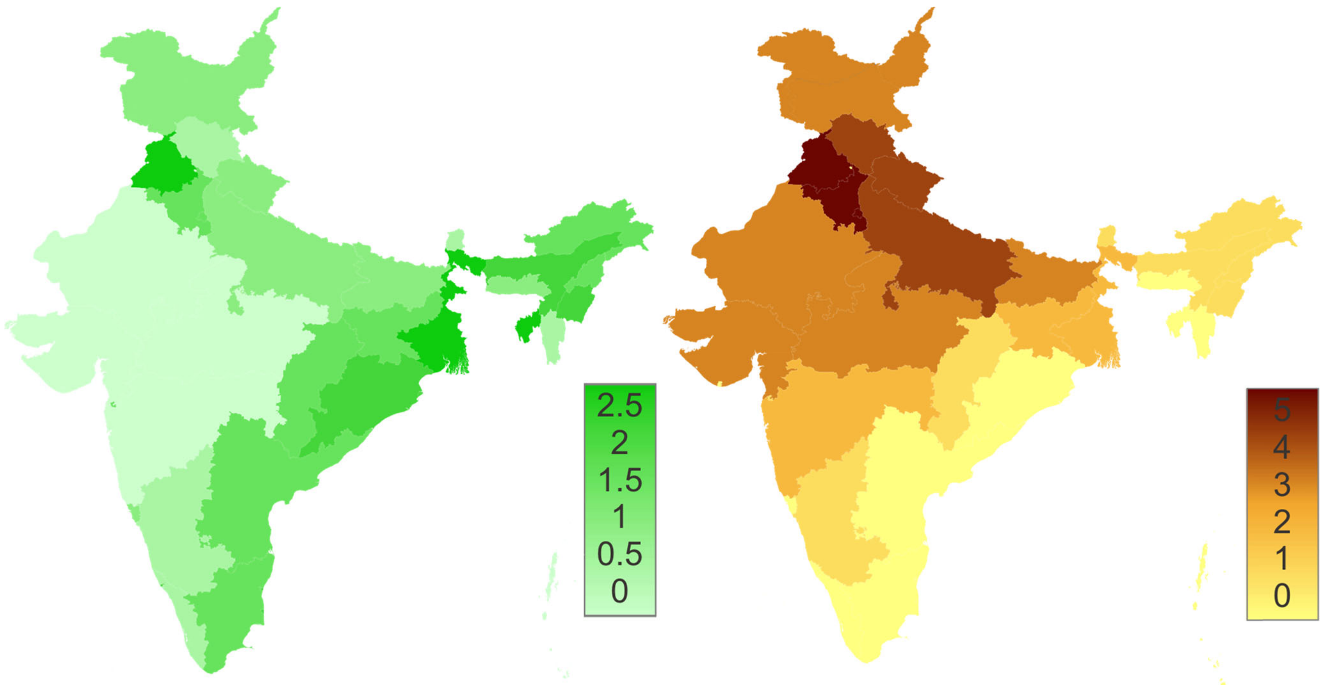


Fig. 4 Yearly production (tonnes) of rice (*left*) and wheat (*right*), normalized by net area sown (hectares). This is not the same as yield as it is not normalized by gross area sown (hectares). This instead illustrates the productivity of agricultural lands both in terms of yields and multiple growing seasons

where A_I is the *State-, season-, and crop-specific* area irrigated, A_I^* is the *State- and season-specific* area irrigated, A_{Source}^* is the *State- and season-specific* area irrigated with the irrigation source denoted by the subscript, and A_{Source} is the calculated *State-, season-, and crop-specific* area irrigated with the irrigation source denoted by the subscript.

Table 1 Variables used in Methods

Primary variable	Derived variable
Gross Area Sown (A_S) Gross Area Irrigated* (A_I^*)	Gross Area Irrigated by *Source* (A_{Source})
Gross Area Irrigated (A_I) Gross Area Irrigated by *Source** (A_{Source}^*) Yield of Irrigated fields in *Year* (Y_I^{year})	
Yield of Non-irrigated fields in *Year* (Y_N^{year}) Irrigation Coefficient in *Year* (C_I^{year})	Irrigation Coefficient (C_I)
Yield of fields irrigated with canals** (Y_{Canal}^{**}) Yield of fields irrigated with public tube wells** (Y_{Public}^{**})	Groundwater Coefficient (C_{GW})
Yield of fields irrigated with water purchases from tube wells** ($Y_{Purchases}^{**}$)	
Yields of fields irrigated with privately owned tube wells** ($Y_{Private}^{**}$)	
Production (P)	Yield of Non-irrigated fields (Y_N)
	Yield of Irrigated fields (Y_I)
	Production from Irrigated fields (P_I)
	Yield from fields irrigated with Surface Water (Y_{SW})
	Yield from fields irrigated with Groundwater (Y_{GW})

Data variables are *State-, season-, and crop-specific* unless otherwise noted: (*) denotes a variable that is only State specific, and (**) denotes a variable that is only crop specific. Derived variables often employed *State-, season-, and crop-specific* variables, and others that are either only *crop-specific* or *State-specific. Source* represents either groundwater, surface water or any of the three surface water irrigation schemes: canals, tanks, and other. *Year* represents a single year ranging from 1989 to 2006

Irrigation coefficient

We calculated the *State-, season-, and crop-specific Irrigation Coefficient* (C_I) as the ratio of irrigated yield to non-irrigated yield. Figures 5 and 6 show the irrigation coefficients for wheat and rice (wet) for selected States in selected years with available data, ranging from 1989 to 2006. Although yields may have changed in the past years, the irrigation coefficient is relatively constant within each State, and the coefficients of variation are presented in Figs. 5 and 6. For the States with available data, we defined the *season- and crop-specific* irrigation coefficient as the average irrigation coefficient over all years with available data:

$$C_I = \text{average}\left\{C_I^{\text{year}} | \text{all years with available data}\right\}$$
$$= \text{average}\left\{\frac{Y_I^{\text{year}}}{Y_N^{\text{year}}}\right\} \quad (2)$$

where Y_I^{year} and Y_N^{year} are the *State-, season-, and crop-specific* yields for irrigated and non-irrigated fields

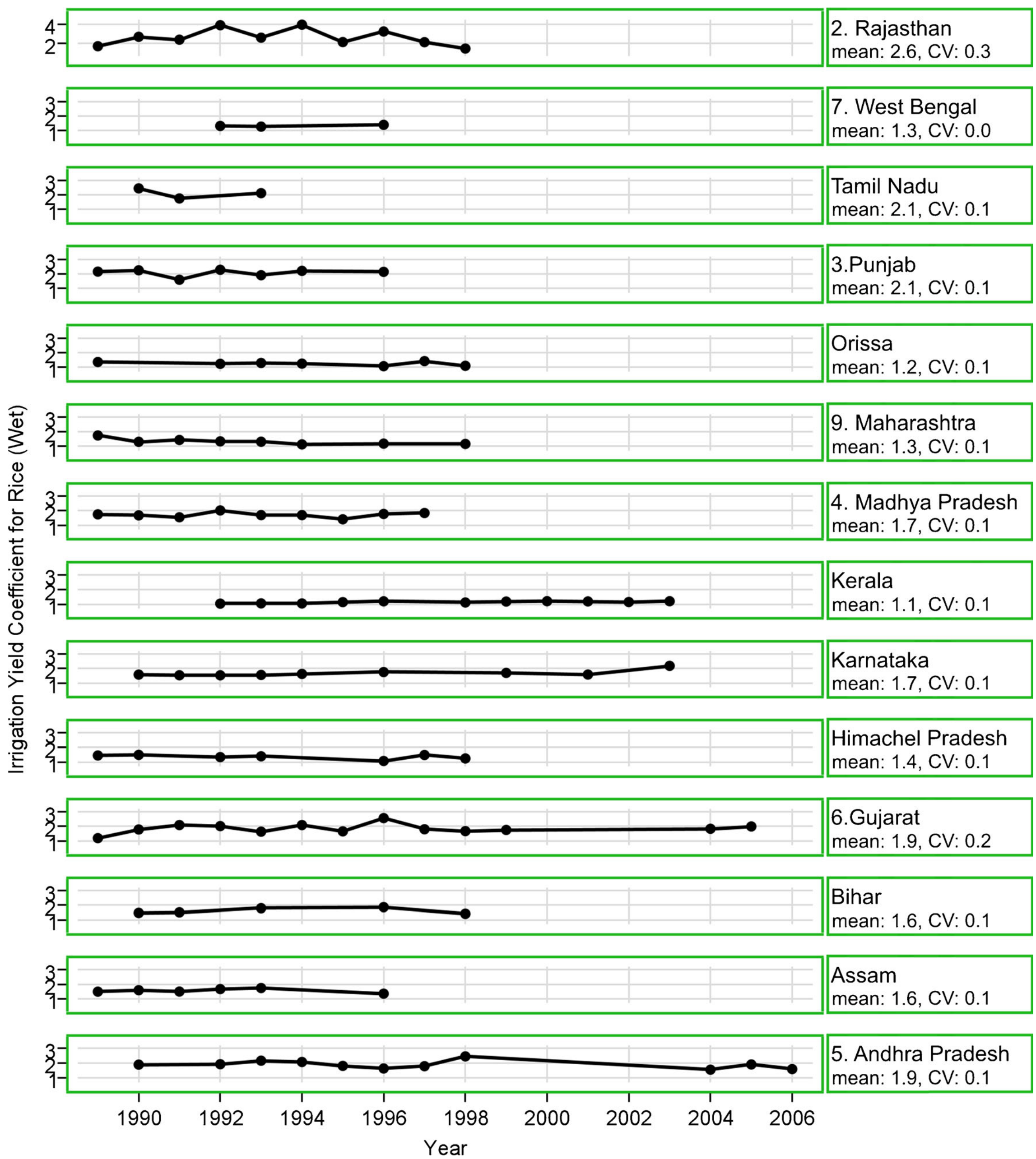


Fig. 5 The irrigation coefficients of rice (wet) for the years 1989–2006 for select States. The numbers for the States refer to the map in Fig. 2 and it should be noted that all vertical scales are the same except Rajasthan which has significantly higher irrigation coefficients

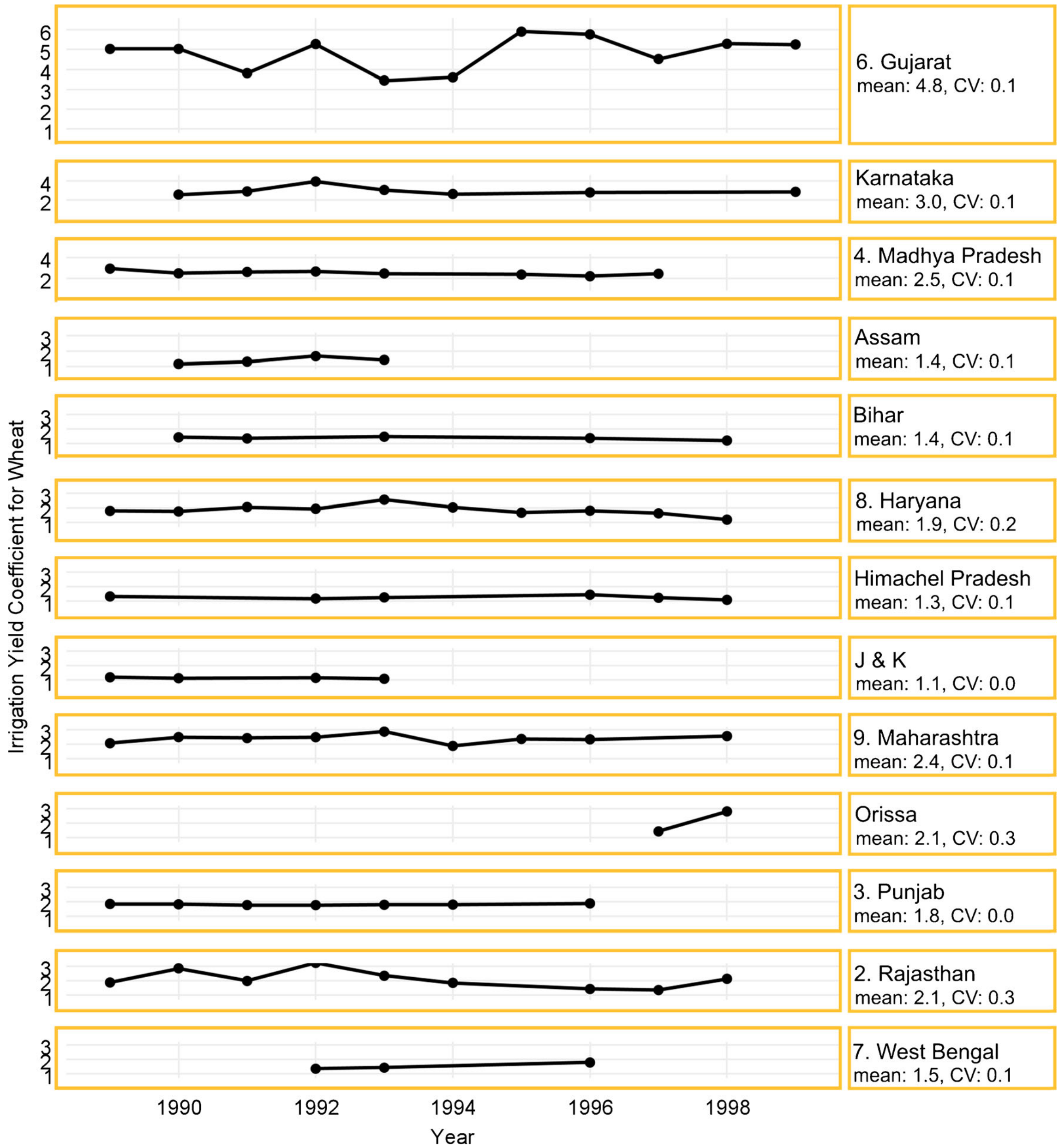


Fig. 6 The irrigation coefficients of wheat for the years 1989–1999 for select States. The numbers for the States refer to the map in Fig. 2 and it should be noted that all vertical scales are the same except Gujarat which has significantly higher irrigation coefficients

respectively, and C_I^{year} is the *State-, season-, and crop-specific* irrigation coefficient in the year denoted by the superscript.

For the States without such data, we defined the irrigation coefficient for both rice and wheat by taking the average of all *crop-specific* irrigation coefficients for the States with available data. A possible alternative definition for the irrigation coefficient is the quotient of irrigated yield and total yield. However, this definition is influenced both by the difference in yields from irrigated and non-irrigated fields, as well as the proportion of agricultural lands that are irrigated. Our definition allows us to isolate the increases in yields on agricultural lands that result from irrigating, and establish a coefficient that is not year-dependent or sensitive to the changes in the proportion of agricultural lands that are irrigated.

We compared and validated the *State-, season-, and crop-specific* irrigation coefficients developed in this study with irrigation coefficients derived from the Global Crop Water Model (GCWM) (Siebert and Döll 2010). The State-averaged irrigation coefficients from GCWM along with those derived in this study in Table 2 for the six States producing the most rice (60 % of India's total rice production) and the six States producing the most wheat (88 % of India's total wheat production) are presented. To compare irrigation coefficients appropriately between the two studies, we calculated the

Table 2 Irrigation coefficients as calculated in this study and derived from the GCWM, and the relative difference between the two

	Rice						Wheat					
State	Andhra P.	W. Bengal	Uttar P.	Punjab	Orissa	Chhattisga.	Uttar P.	Punjab	Haryana	Madhya P.	Rajasthan	Bihar
C_I: This study	1.88	1.33	1.68	2.08	1.25	1.68	2.10	1.82	1.85	2.50	2.12	1.38
C_I: GCWM	2.01	1.37	2.33	7.24	1.56	1.61	2.06	1.79	1.61	1.13	1.84	1.13
Relative Difference	0.07	0.03	0.32	1.11	0.22	0.04	0.02	0.01	0.14	0.76	0.14	0.20

State- and crop-specific relative differences (Table 2) and found that the irrigation coefficients derived from the two approaches were similar. Further details on the methods used for the comparison are available in the Supplementary material.

With our methods and the available data, the difference in non-irrigated and irrigated yields could not be attributed solely to irrigation. High-yielding varieties of crops necessitate access to irrigation technologies, and such crops are highly responsive to increased inputs, and are no more productive, or perhaps even less productive than traditional varieties in the absence of such inputs (Shiva 1991). Further, well owners and those with access to irrigation make greater investments in complementary inputs such as fertilizers and labour (Kahnert and Levine 1993). The higher yields from irrigated lands must therefore be attributed not only to irrigation water use, but also to the possible use of high-yielding varieties of seeds and other inputs. In this way, the crop varieties, inputs, and agricultural practices available and employed on non-irrigated and irrigated lands in each State, and the effect on yields are implicit in our methods and chosen datasets. Explicitly examining these factors further, however, was not possible with the given data and is beyond the scope of this analysis.

Groundwater coefficient

The *Groundwater Coefficient* (C_{GW}) was calculated as *crop-specific*, defined as the quotient of the yield from fields irrigated with groundwater and the yield from fields irrigated with surface water. Farmers irrigating with groundwater are generally more able to control both the timing and amount of irrigation than farmers irrigating with public surface water schemes. Groundwater irrigated crops produce between 30 and 50 % more than areas irrigated with surface water (Dhawan 1995). Groundwater irrigated fields have also been documented to use (withdraw) four times less water than similar fields irrigated with surface water (Llamas and Custodio 2003). We can then estimate crudely that groundwater is between five and six times more economically / water productive than the same volume of surface water. A comparison among irrigation sources in Andalusia, Spain (Hernandez-Mora et al. 2001) found that groundwater was five times more economically productive than the same volume of surface water, and that groundwater irrigation generated three times more employment than surface water irrigation (Llamas and Custodio 2003). We used a more conservative estimate of *crop-specific* yields resulting from different irrigation sources from a study in Pakistan (Lowdermilk et al. 1978) (Table 3). We did not use the specified yields, but rather developed relationships between yields from various irrigation sources. These estimates were used even though they were not derived directly from India as they are one of the few systematic studies (Giordano and Villholth 2007; Shah 1993, 2010) from a nearby and similar agricultural system (Cheema et al. 2014).

Farmers owning private tube wells tend to have higher yields than those purchasing water from tube wells, and those purchasing water from tube wells tend to have higher yield than farmers using public tube wells; all users irrigating with groundwater tend to have higher yields than farmers dependent solely on canals (Table 3). A conservative weighted average of the yields from the three different categories of groundwater irrigation schemes was determined

Minor irrigation is defined in India as any irrigation scheme that waters less than 2000 ha (Government of India 2011); groundwater irrigation is in the category of minor irrigation. For these calculations we drew on data provided by the third minor irrigation census of 2000–01 (Ministry of Water Resources 2001a, b). Individuals or farmer collectives often finance groundwater schemes, while minor irrigation surface water projects are usually financed by the public sector (Government of India 2011): 86.8 % of fields under minor irrigation schemes used groundwater and 12.5 % of fields under minor irrigation schemes were public (Ministry of Water Resources 2001a, b). To conservatively estimate the maximum percentage of public tube wells, we assume that 12.5 %

Table 3 Sources of irrigation water and the corresponding yields (kg/ha) of wheat and rice

	Canal only (Y_{canal})	Public tube well (Y_{public})	Water purchases ($Y_{purchases}$)	Private tube well ($Y_{private}$)
Wheat	1660.5	1845.9	1937.3	2214.1
Rice	1289.9	1752.0	1937.3	2122.6

of the groundwater irrigated fields were public, namely, we assume 10.8 % (=12.5 % of 86.8 %) of fields under minor irrigation schemes were irrigated with public tube wells. This is certainly an inflated maximum and therefore conservative upper limit as aforementioned public investments have focused largely on surface water infrastructure.

According to the findings of Singh (2003), large-scale landowners only sold water and did not purchase from other tube wells. We conclude that large land holdings fall into the "private tube well" category. Large land holdings made up 10.9 % of all cultivated area in India in the 2010–11 growing season (Ministry of Agriculture 2011) and we can therefore assume that a minimum of 10.9 % of cultivated area was irrigated with private tube wells.

The groundwater coefficient (C_{GW}) was calculated specifically as the quotient of the conservative weighted average (maximizing hectares irrigated with public tube wells and minimizing hectares irrigated with private tube wells) of the three groundwater-irrigated yields and the canal yield:

$$C_{GC} = \frac{0.108\cdot\left(Y^{**}_{Public}\right) + .109\cdot\left(Y^{**}_{Private}\right) + 0.783\cdot\left(Y^{**}_{Purchases}\right)}{\left(Y^{**}_{Canal}\right)} \quad (3)$$

Where Y^{**}_{Public}, $Y^{**}_{Private}$, $Y^{**}_{Purchases}$, and Y^{**}_{Canal} are the *crop-specific* yields for fields irrigated with water from public tube wells, private tube wells, water purchased from tube wells, and water from canals respectively (Table 3).

The groundwater coefficient is 1.49 for rice and 1.16 for wheat.

Production

State-, season-, and crop-specific production (P) of rice and wheat grains were partitioned into the production from fields irrigated with groundwater, irrigated with surface water, and non-irrigated. From the previous calculation of the irrigation coefficients we have:

$$Y_N\cdot C_I = Y_I \quad (4)$$

where Y_N and Y_I are the *State-, season-, and crop-specific* non-irrigated and irrigated yields respectively.

Similarly,

$$Y_{SW}\cdot C_{GW} = Y_{GW} \quad (5)$$

where Y_{SW} and Y_{GW} are the *State-, season-, and crop-specific* surface water irrigated and groundwater irrigated yields respectively.

We will solve for Y_N, Y_I, Y_{SW}, and Y_{GW}

State-, season-, and crop-specific yield from fields non-irrigated and irrigated were calculated as follows:

$$\begin{aligned} P &= A_I\cdot Y_I + (A_S - A_I)\cdot Y_N \\ &= A_I\cdot Y_N\cdot C_I + (A_S - A_I)\cdot Y_N \\ &= Y_N\cdot[A_I\cdot C_I + (A_S - A_I)] \end{aligned} \quad (6)$$

where A_S is the *State-, season-, and crop-specific* gross area sown.

The variables are rearranged to solve for the only unknown, the non-irrigated yield:

$$Y_N = \frac{P}{A_I\cdot C_I + (A_S - A_I)} \quad (7)$$

We can now calculate the rice and wheat grain production from irrigated fields:

$$P_I = Y_I\cdot A_I = Y_N\cdot C_I\cdot A_I \quad (8)$$

where P_I is the *State-, season-, and crop-specific* production from irrigated fields.

State-, season-, and crop-specific yield from fields irrigated with groundwater and surface water were calculated by a similar procedure, and we established the yield of crops irrigated with surface water as follows:

$$Y_{SW} = \frac{P_I}{A_{GW}\cdot C_{GW} + (A_I - A_{GW})} \quad (9)$$

With *State-, season-, and crop-specific* yields for rice and wheat grains calculated for fields irrigated with groundwater, irrigated with surface water, and non-irrigated, and previously calculated *State-, season- and crop-specific* areas sown with rice or wheat and irrigated with groundwater, irrigated with surface water, or non-irrigated, we can partition rice and wheat grain production *State-, season-, and crop-specific* into the production from fields irrigated with groundwater, irrigated with surface water, and non-irrigated.

Potential production

Both the increase in production that would occur if all fields sown with rice or wheat were irrigated and the loss if all fields were non-irrigated were calculated. In the first two scenarios we assumed that all currently irrigated fields continue to be irrigated with their current irrigation source. In the first scenario we assumed that the currently non-irrigated fields were irrigated with irrigation sources proportional to the current *State- and crop-specific* use of irrigation sources on irrigated lands sown with rice or wheat. In the second scenario we assumed that all currently non-irrigated fields were irrigated with groundwater. In scenario 2, if a State currently has no groundwater irrigation, we followed the distribution of scenario 1. In both scenarios, we assumed the current proportional distribution of agricultural fields using particular crop varieties and agricultural inputs was the same when irrigation was expanded to currently non-irrigated fields. In scenario 3, we assumed there was no irrigation on fields sown with rice or wheat (see Fig. 7 for further explanation).

First scenario:
State-, season-, and crop-specific production were calculated:

$$P = A_S \cdot Y_I \qquad (10)$$

Second scenario:
Post-1970, State-electricity utilities switched over to flat-rate tariffs as a matter of convenience as the administrative costs associated with monitoring, billing, and collecting fees consumed 30 % of the cost of supplying power for extraction of water from groundwater wells (World Bank 2001; Shah 1993). Currently, State policy and State power utility regulations range from full-cost unsubsidized electricity (as in West Bengal) to heavily subsidized or free electricity for agricultural users with only low flat-rate tariffs (as in Gujarat, Punjab, Andhra Pradesh, Karnataka, Haryana, Rajasthan, Madhya Pradesh, Maharashtra, and Tamil Nadu), although the latter is more representative of most States (World Bank 2001; Meenakshi et al. 2012; Mukherji 2006, 2012; Mukherji et al. 2012a, b; Shah et al. 2008). The re-introduction of metered consumption is seen both as the ideal "text-book solution" for India's groundwater management, but also far-fetched from the administrative, utility, and political points of view (Shah et al. 2008; Nair and Shah 2012; Mukherji et al. 2012b). Political discussion of universal metering has been subdued as farmer groups have been able to mobilize considerable pressures against metered tariffs. Politicians have instead used the promise of flat-rate tariffs as an electoral tool so as not to undermine or risk damaging their political power and presence (World Bank 2001; Mukherji 2006; Mukherji et al. 2012b; Shah et al. 2008).

$$P = (A_S - A_I) \cdot Y_{GW} + A_I \cdot Y_I \qquad (11)$$

Third scenario:
This scenario is not motivated by trends in India's irrigation development, but simply meant to complement the first two scenarios. The calculation frames our understanding of the relationship between irrigation water resources and agricultural production. Scenarios 1 and 2 provide estimates of agricultural production under the assumption that all agricultural fields are irrigated, and scenario 3 provides an estimate for agricultural production under the assumption that no agricultural fields are irrigated. Together, the scenarios provide us with a range of agricultural production from zero to maximum consumption of irrigation water.

$$P = A_S \cdot Y_N \qquad (12)$$

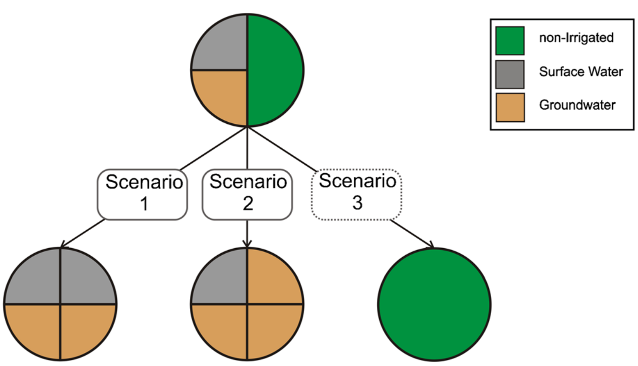


Fig. 7 This figure is designed to help visualize the three scenarios described in the text more easily. The top circle represents a hypothetical situation, with an arbitrary distribution of irrigation water illustrated as 25 % surface water and 25 % groundwater and 50 % non-irrigated. In scenario 1, the proportion of each irrigation source used on the irrigated fields (top circle) is applied to the non-irrigated fields giving 50 % surface water and 50 % groundwater. In scenario 2, all the non-irrigated fields are irrigated with groundwater, resulting in 25 % surface water and 75 % groundwater. In scenario 3, all fields are non-irrigated. Scenario 3 is not motivated by trends in India's agricultural development, but calculated to complement the two previous scenarios: it is agricultural production with zero irrigation water use, while scenarios 1 and 2 provide the calculation for agricultural production with maximum use of consumptive irrigation water

Increases in irrigation water consumption

The increased consumption of irrigation water from irrigating all non-irrigated lands sown with rice and wheat, as well as total irrigation water consumption, was estimated using the GCWM, and is representative of the year 2000. A description of the model is available in Siebert and Döll (2010). The gross area sown with rice and wheat in the 2010–11 growing season was 96 and 113 % respectively of the area sown in the 2000–01 growing season. The gross area irrigated increased for both rice and wheat in the 2010–11 growing season, by 5 and 21 %, respectively. We scaled the *State- and crop-specific* irrigation water consumption from the year 2000 proportionally with the *State- and crop-specific* changes in gross area sown and gross area irrigated. There were sometimes appreciable differences between the datasets used for the development of this study (Census statistics made available by the Government of India and various departments associated with State governments) and that associated with the water estimates from the year 2000 (MIRCA2000) with respect to the *State- and* *crop-specific* areas sown or irrigated. To account for this, we first scaled the *State- and crop-specific* water estimates for the year 2000 by the *State- and crop-specific* ratios of the areas sown/irrigated according to the datasets used in this study to the areas sown/irrigated according to MIRCA2000.

Results

Area

India sows nearly two hundred million hectares of land with crops, 22 % rice and 15 % wheat; of all sown land, 44 % is irrigated. This 44 % average is, however, unevenly distributed: 60 % of fields sown with rice, 93 % of fields sown with wheat, and 28 % of other crops are irrigated (Table 4). Groundwater provides irrigation for 65 % of the total gross area irrigated, again unevenly distributed: slightly less for rice (groundwater is the irrigation source for nearly 60 % of the irrigated gross area sown with rice), slightly more for wheat (71 %), and significantly less for other crops (25 %) (Table 4).

The average water requirement for rice in India, depending on both climatic region and seed variety, is between 750 and 2500 mm per season, with average consumption between 300 and 950 mm (Ministry of Agriculture 2001). An average of 49 % of the irrigated land sown with rice, and 62 % of the groundwater-irrigated land sown with rice receive less than 750 mm of rain during the wet season, 71 and 58 % respectively averaged over both growing seasons (Fig. 8).

The average water requirement for wheat in India, depending on both climatic region and seed variety, is between 400 and 900 mm, with average consumption between 300 and 450 mm (Ministry of Agriculture 2001). An average of 98 % of the irrigated land sown with wheat, and 99 % of the groundwater-irrigated land sown with wheat receive less than 200 mm of rain during the dry season (Fig. 8).

Current and potential production

The 60 % of the gross area sown with rice that is irrigated accounts for 73 % of total rice production, and the 93 % of the gross area sown with wheat that is irrigated accounts for 97 % of total wheat production. The 35 % of gross area sown with rice that is irrigated with groundwater accounts for 49 % of the total rice production, and the 66 % of gross area sown with wheat that is irrigated with groundwater accounts for 72 % of the total wheat production (Table 5; Fig. 9). Figure 9 illustrates the relationship between production and irrigation sources for select States highlighting that the distribution of irrigation sources is not necessarily paralleled by production within the State, i.e., groundwater irrigation generally produces proportionally more than surface water irrigation which produce proportionally more than non-irrigated agriculture.

We calculated the potential increase in production that would occur if all land currently sown with rice or wheat were irrigated, and studied two possible scenarios for this development. Rice production would increase by 14 and 25 % in scenarios 1 and 2, respectively, and therefore production potential is currently between 86 and 75 %, respectively. Wheat production would increase by a mere 3 % in both scenarios, and therefore production potential is currently at 97 %. India has therefore nearly closed its yield gap for this crop (Table 6; Fig. 10).

In both scenarios, the gross area sown with rice and irrigated increases by 67 % and for wheat by 8 % (Table 5). Potential production, however, is significantly different when viewed at the State-level: rice production can increase 59–130 % for Assam, with a production increase between 2774 and 6175 thousand tonnes, and wheat production can increase 18–20 %

Table 4 Percentage of gross crop area irrigated by irrigation source. Area is in 1000 ha

		GW	Canals	Tanks	Other	Total	Hectares (Thousands)
All Crops	% of irrigation	65	28	2	5	100	88,252
	% of land sown	29	13	1	2	44	198,609
Rice (Wet)	% of irrigation	60	31	3	6	100	21168.1
	% of land sown	34	18	2	3	56	37735.8
Rice (Dry)	% of irrigation	51	33	8	9	100	4539.9
	% of land sown	45	29	7	8	89	5126.7
Rice Total	% of irrigation	58.5	31.6	3.8	6.1	100	25,708
	% of land sown	35	19	2	4	60	42862.5
Wheat	% of irrigation	71	25	1	3	100	27,471
	% of land sown	66	23	1	3	93	29628.4
Non-Rice, non-Wheat	% of irrigation	64	29	3	4	100	35,073
	% of land sown	18	8	1	1	28	126,118

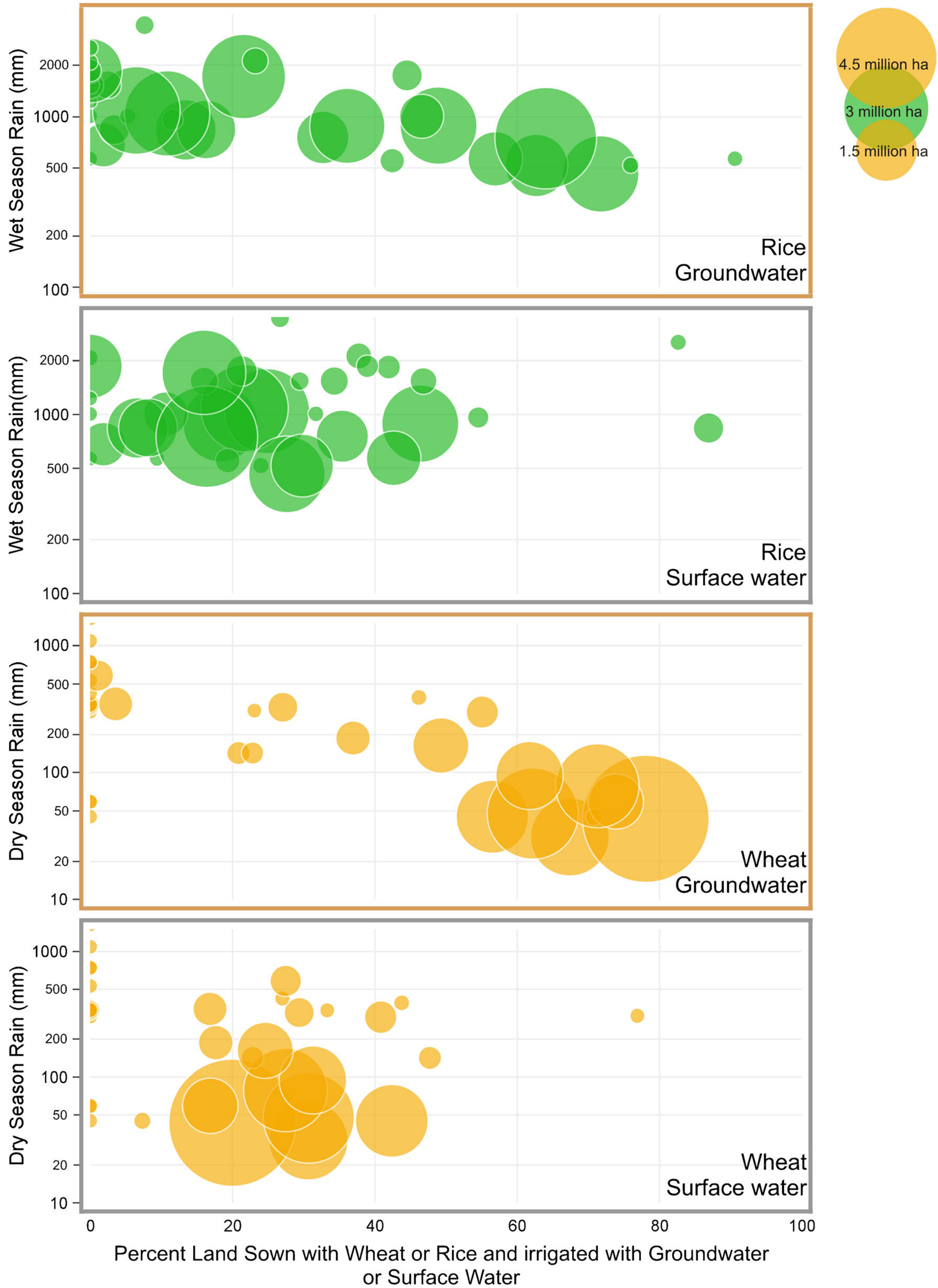


Fig. 8 Each *circle* represents a State, and the *size of a circle* is reflective of the gross area sown with the associated crop in the associated State. A power function with an exponent of 0.42 is used to relate gross area sown to circle area to facilitate visualization

for Maharashtra with a production increase between 441 and 449 thousand tonnes (Table 7; Fig. 10).

Each scenario results in a different *State-, season-, and crop-specific* version of potential yield, and similarly different

Table 5 Percentage of crop production resulting from each irrigation source. Production is in 1000 tonnes and area is in 1000 ha

		GW	Canals	Tanks	Other	Total	Production Area
Rice (Wet)	% of production	47	16.5	1.5	3	68	80,667
	% of land sown	34	18	2	3	56	37,736
Rice (Dry)	% of production	58	26	6	6	96	15,312
	% of land sown	45	29	7	8	89	5127
Rice Total	% of production	49	18	2	4	73	95,979
	% of land sown	35	19	2	4	60	42,863
Wheat	% of production	72	22	1	2	97	86,874
	% of land sown	66	23	1	3	93	29,628

The last column representing production and area, are the total production and total area for the respective crops in India, for example, rice (wet) production in India resulting from irrigation is 68 % of 80,667,000 tonnes

estimates on the current status with respect to possible production potential: total rice production is currently between 88 and 80 % of production potential under scenarios 1 and 2 respectively, and wheat production is at 97 % of production potential under both scenarios (Fig. 10).

Increases in irrigation water consumption

The increase in consumption of irrigation water from irrigating non-irrigated fields for the 2010–11 growing season is estimated at 31 % (30.9 km^3/year) for rice and 3 % (3.2 km^3/year) for wheat. The largest increases in irrigation water consumption for rice would be in Chhattisgarh, Uttaranchal, West Bengal, and Bihar, and for wheat in Himachal Pradesh, Uttar Pradesh, Uttaranchal, and Maharashtra. The total estimated irrigation water consumption for the 2010–11 growing season, if all fields were irrigated, is estimated at 131 km^3/year for rice and 105 km^3/year for wheat.

Sensitivity of irrigation and groundwater coefficients on potential production

The three estimates for rice and wheat production changes under the different scenarios are dependent on the *State-, season and crop-specific* irrigation coefficients, and the *crop-specific* groundwater coefficients. Our sensitivity analysis varied the *State- and crop-specific* irrigation and groundwater coefficients by increasing and decreasing each value by up to 10 %.

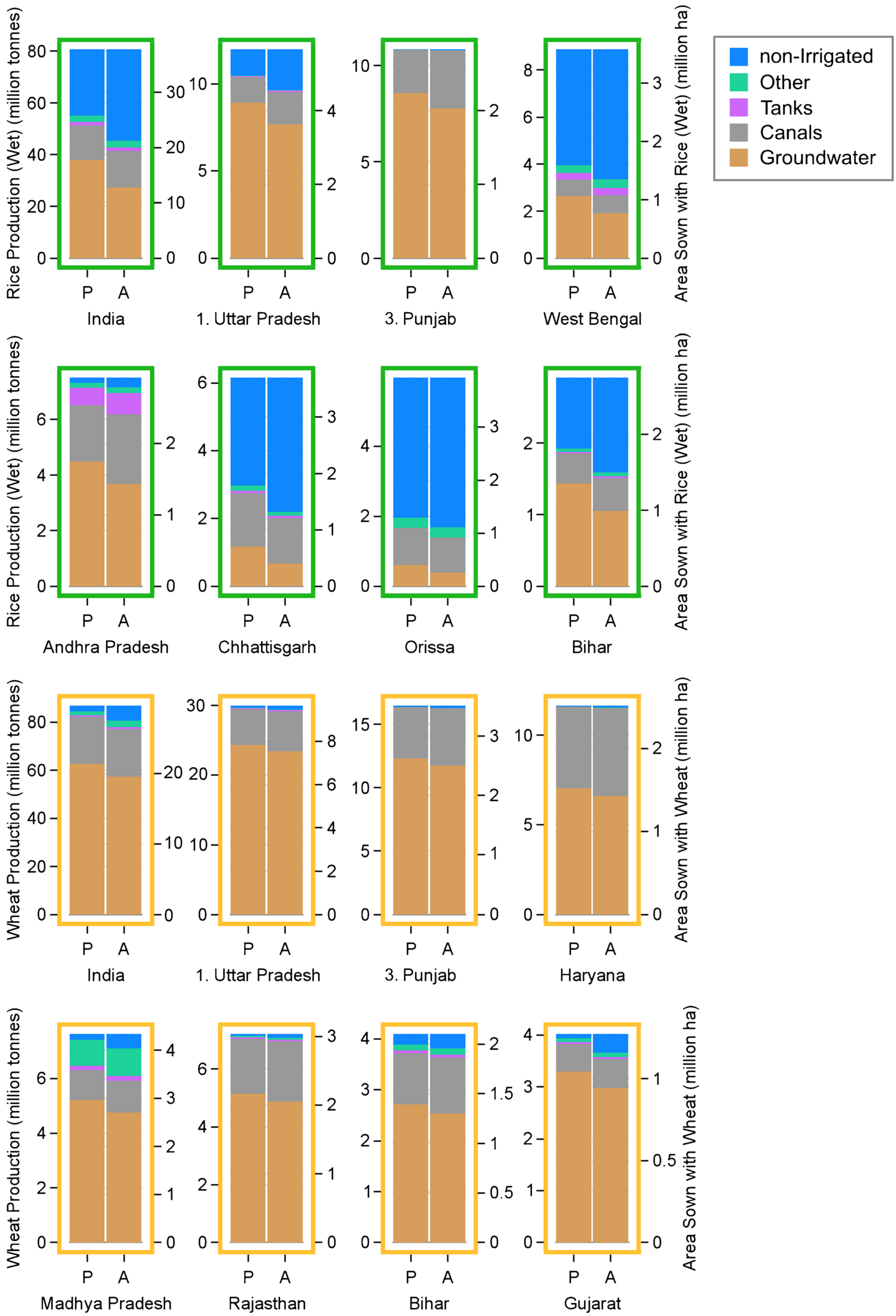
Scenarios 1 and 3 employed only irrigation coefficients while scenario 2 employed both the irrigation and groundwater coefficients. Decreasing and increasing all *State- and crop-specific* irrigation coefficients by 10 % estimates that rice production would increase by 11.3–17.4 % (as compared to 14 %) under scenario 1, and be at 71.6–79 % of current production (as compared to 75 %) under scenarios 1 and 3 respectively (Fig. 11, Table 8). Similarly for wheat, varying the irrigation coefficients by 10 % estimates that wheat production would increase by 2.6–3.3 % (as compared to 3 %), and be at 46.6–56.4 % of current production (as compared to 51 %) under scenarios 1 and 3 respectively (Fig. 11, Table 8). Increasing both the irrigation and groundwater coefficients by 10 % for Scenario 2 estimates that rice production would increase between 17.8 and 32.8 % (as compared to 25 %) and wheat production would increase between 2.4 and 3.6 % (as compared to 3 %) (Figs. 11 and 12, and Tables 8 and 9).

Potential production shows limited sensitivity to the irrigation and groundwater coefficients. The irrigation coefficients were calculated for rice explicitly in 14 States (representative of 73 % of all rice production) and for wheat explicitly in 13 States (representative of 59 % of all wheat production), wherever the necessary data were available. The other States were assigned the average *crop- and season-specific* irrigation coefficient. Comparison of *State- and crop-specific* irrigation coefficients with those calculated from Siebert and Döll (2010) show good agreement, and the coefficient of variation from States with available data range between 0 and 0.3 with the majority equal to 0.1. The groundwater coefficients were calculated conservatively and may underestimate the estimates on current production irrigated by groundwater, as well as the potential production increases in scenario 2.

Discussion

India is intensively using surface and groundwater resources for agricultural production. Our estimates determine the

Fig. 9 The production (P) and area sown (A) for different irrigation ▶ sources in different states where each pair of *stacked bars* is associated with a State. The upper part of the figure is for rice and the lower part of the figure is for wheat. The total height of each *left stacked bar* is the total production of the associated crop (P), and the total height of each *right stacked bar* is the gross area sown with the associated crop (A)


Rice Production (Wet) (million tonnes)
Area Sown with Rice (Wet) (million ha)
Wheat Production (million tonnes)
Area Sown with Wheat (million ha)
non-Irrigated
Other
Tanks
Canals
Groundwater
P
A
India
1. Uttar Pradesh
3. Punjab
West Bengal
Andhra Pradesh
Chhattisgarh
Orissa
Bihar
Haryana
Madhya Pradesh
Rajasthan
Gujarat

increase in production from irrigating currently non-irrigated fields. Even without considering water availability as a potential limiting factor, our results show a smaller production potential than previous estimates (see next paragraph); our calculations are therefore estimated maximum potential increases subject to water availability. Our calculations on potential production loss assumes implicitly that fields currently irrigated would be able to sustain crop growth, but with the crop variety, inputs, and agricultural practices associated with the representative non-irrigated fields of the State. Our estimate should therefore be seen as a minimum loss scenario, as lands currently irrigated may not in reality have the adequate precipitation to continue crop production. These estimates are also under average rain and climate conditions. In the event of a drought, estimates for production change under the three scenarios would be drastically different as irrigation water would become the primary source of meeting crop water requirements, and the currently non-irrigated fields would be without the necessary means to protect crop production. Irrigation can both augment water supply and provide a buffer in times of precipitation and climate uncertainty (Llamas and Custodio 2003; Ribot et al. 1996).

Licker et al. (2010) estimated that for India, rice production is at 46 % of potential and wheat production is at 67 % percent of potential, the estimates being based solely on the notion of climatic potential. Our methods estimate production potential at 80–88 % and 97 % for rice and wheat, respectively, calculated as the increases in yields due to introducing irrigation on non-irrigated fields, and implicitly incorporates the inputs and investments often associated with irrigated fields (Kahnert and Levine 1993). Assuming the estimates of Licker et al. (2010), our estimates can be used to partition the increases in production attributed to irrigation (and the associated *State-specific* inputs and investments): with rice currently at 46 % of production potential and wheat at 67 % of production potential, if each State were to irrigate all non-irrigated fields, but restrict themselves to the inputs, crop varieties, and management practices currently available and adopted within each State, rice would still be only between 52 and 58 % (14–25 % increase over the current 46 %) of production potential and wheat would be at 69 % (3 % increase). The significant yield gap that remains is then not directly related to increasing the use of water resources, although the adoption of certain crop varieties may necessitate an increase in water use.

Scenarios 1 and 2 are motivated by trends in India's agricultural landscape and represent potential futures for irrigation in India. Seckler (1998) has predicted that the rate of current groundwater development in India will lead to the eventual exhaustion of groundwater aquifers, and the inevitable collapse of the associated agricultural economies. Further, farmers are generally not deterred by a concern for the rising abstraction costs typically associated with intensive groundwater use; electricity is largely or completely subsidized by most Indian State power utilities (World Bank 2001; Mukherji 2006, 2012; Mukherji et al. 2012a, b; Shah et al. 2008; Fishman et al. 2011; Meenakshi et al. 2012; Nair and Shah 2012). In the past several decades, groundwater development has significantly helped to alleviate poverty, improve public health (Llamas and Custodio 2003), support livelihood development in poor areas (Shah et al. 2000), and provide sustenance for millions of agricultural and non-agricultural rural livelihoods (Shah et al. 2003). However, the intensive use of groundwater has resulted in declining water tables, compromised water quality, reduced base flow, and threatens the viability of irrigated agriculture in India (Custodio and Llamas 2003; World Bank 2010a; Fishman et al. 2011; Gleeson et al. 2012; Gleeson and Wada 2013).

Limited gains from further expansion of irrigation, increasing competition for water resources, and a significant portion of rice and wheat grain production lost under non-irrigated conditions prompts the idea that irrigation expansion may be an inappropriate effort towards food security. Instead, efforts should be towards securing irrigation water for years of drought and climatic variability and employing water resources as a supplementary instead of a primary source for meeting crop water. This more conservative use of resources would both protect the base production of rice and wheat grains in years of climatic variability, and encourage the recovery of water resources in aquifers which have had long-term reductions in groundwater levels. However, this approach must be tailored regionally and by aquifer-type, taking into consideration storage, precipitation, recharge, and capture

Table 6 India production increases under scenarios 1 and 2 compared with non-irrigation. Production is in 1000 tonnes

	Scenario 1		Scenario 2	
	Production increase	Percent increase	Production increase	Percent increase
Rice (Wet)	12,988	16	22,946	28
Rice (Dry)	588	4	1135	7
Rice Total	13,576	14	24,081	25
Wheat	2356	3	2705	3

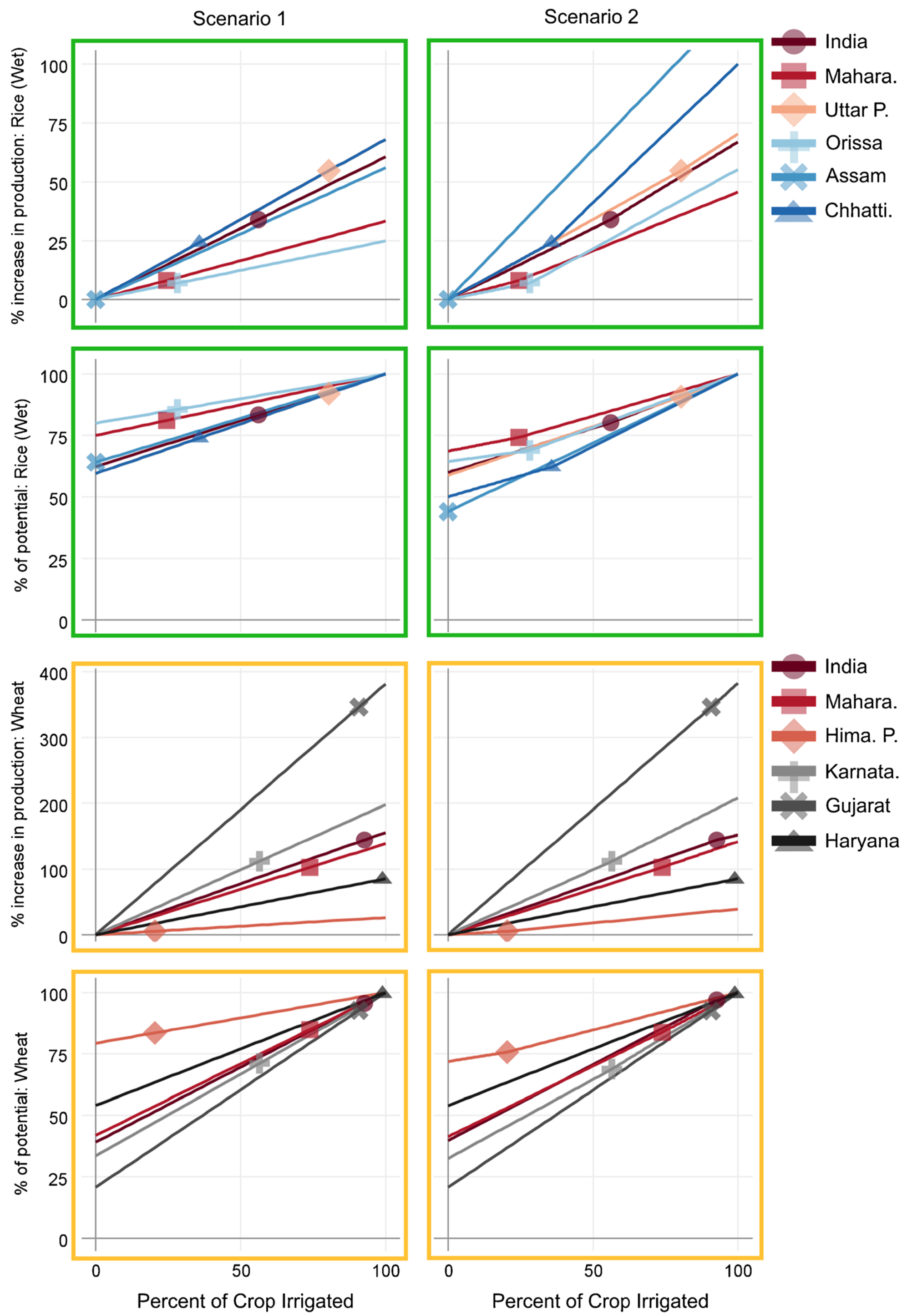


Fig. 10 Scenario 1 is on the left and Scenario 2 is on the right. Each *curve* represents a State, and the associated shape on each curve represents the current situation of that State. Row 1 and 3: The *curves* represent the relationship between gross area irrigated and production increase as compared to the non-irrigated production, for example, under scenario 1, if 50 % of gross land sown with rice (wet) is irrigated, Assam would experience a 28 % increase in rice (wet production) while Uttar Pradesh would experience a 34 % increase as compared to both States with no irrigation. Rows 2 and 4: the *curves* represent the relationship between gross area irrigated and the percent of production potential being achieved, for example, only 20 % of gross area sown with wheat in Himachel Pradesh is irrigated, but it is already at 76 % of its prodution potential

dynamics; and response time with respect to pumping and recharge (Fishman et al. 2011). The spatial distribution of irrigation use and requirements is not even, with the highest in the States with the least precipitation. Irrigation has benefited the economy and social health of these regions, including numerous livelihoods (Siebert and Döll 2010).

A limitation in our study is the absence of information on the conjunctive use of irrigation sources. Conjunctive use of groundwater and surface water sources occurs widely in India, although the use of only a single irrigation source, either surface water or groundwater, is also widespread (World Bank 2010a; Shah 2010; Jain et al. 2007). Datasets used in this paper reported only a single source for irrigated fields, which was either the assumed, initial, or dominant water source. In addition, a growing part of groundwater extraction from shallow aquifers depends on artificial recharge of the aquifers by

Table 7 Select-State production increases under scenarios 1 and 2 compared with non-irrigation. Production is in 1000 tonnes

		Scenario 1		Scenario 2	
		Production increase	Percent increase	Production increase	Percent increase
Rice (Wet and Dry)	Assam	2774	59	6175	130
	Jharkhand	708	64	1058	95
	Madhya Pradesh	878	50	1140	64
	Chhattisgarh	2167	35	3784	61
	Orissa	998	15	2721	40
	West Bengal	1624	12	2708	21
	Whole of India	13,576	14	24,081	25
Wheat	Karnataka	114	41	128	46
	Jharkhand	63	40	73	46
	Uttaranchal	274	31	300	34
	Himachal Pradesh	108	20	182	33
	Chhattisgarh	25	20	31	24
	Maharashtra	411	18	449	20
	Whole of India	2356	3	2705	3

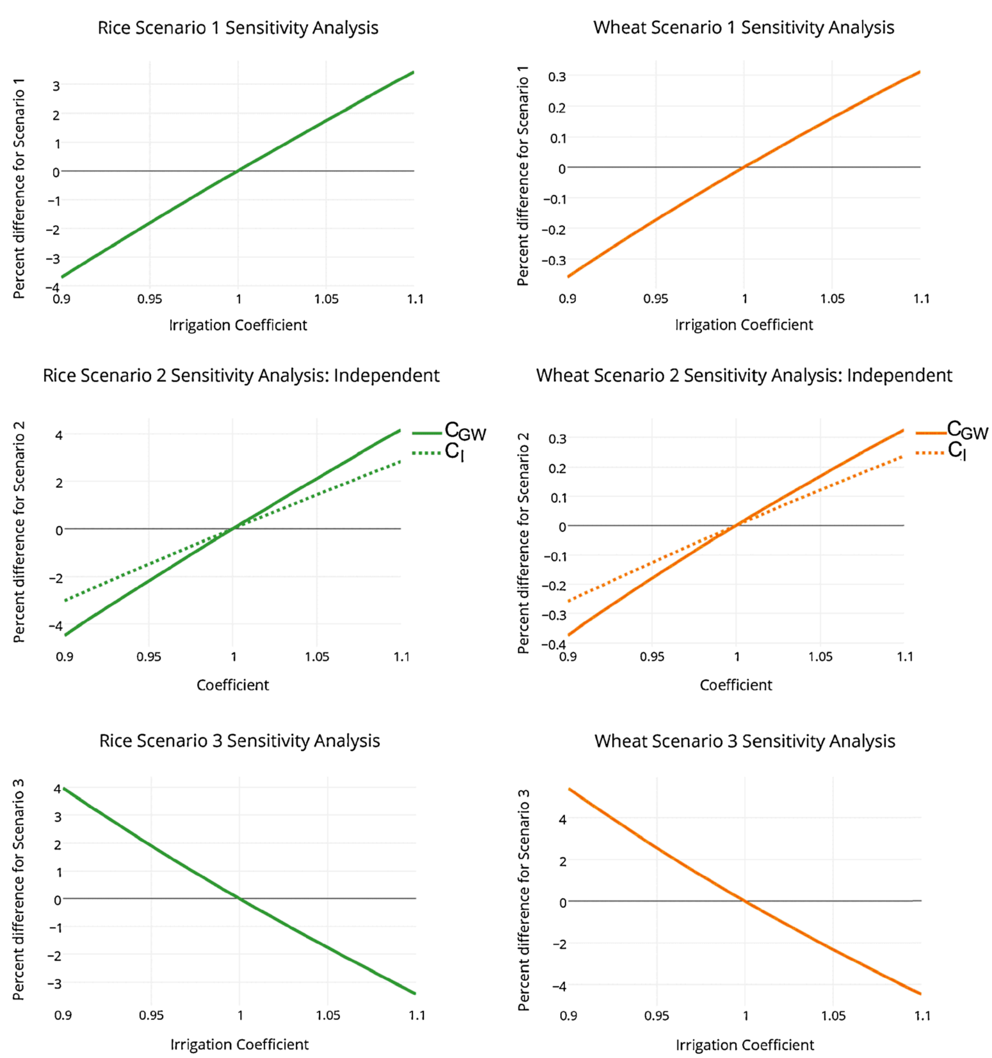


Fig. 11 Sensitivity analysis for scenarios 1–3, independently varying the irrigation and groundwater coefficients. The y-axis is the percent difference from the estimates provided in the article, and the x-axis is the irrigation or groundwater coefficient changed by up to 10 %. The *left column* represents rice, and the *right column* represents wheat. The *three rows* represent scenarios 1–3 respectively

Table 8 Sensitivity Analysis (Independent) for Scenarios 1–3. Values are in percent and are the differences between the original estimates and estimates with the changed coefficient

		C_I −10 %	C_I +10 %	C_{GW} −10 %	C_{GW} +10 %
Rice	Scenario 1	−3.7	3.4		
	Scenario 2	−4.5	4.2	−3	2.8
	Scenario 3	4	−3.4		
Wheat	Scenario 1	−0.4	0.3		
	Scenario 2	−0.4	0.3	−0.3	0.2
	Scenario 3	5.4	−4.4		

less efficient use of surface water for irrigation. These relationships between use of groundwater and surface water for irrigation can only properly be investigated for specific irrigation schemes or watersheds, which is beyond the scope of this article.

Applicability of the method to other areas

This study focused on rice and wheat production in India, but the methods developed may be applied to other crops and to regions in other countries. Data in our methodology are 1) gross area sown (irrigated) per crop, more specifically area sown (irrigated) per season, 2) gross area irrigated by irrigation source, 3) production of crop per season from irrigated fields and from non-irrigated fields, and 4) sufficient documented history for yields from crops for both irrigated and non-irrigated fields. Such data are usually provided by a national or sub-national agricultural census. The advantage of our methodology is that we are able to estimate the contribution of surface water and groundwater to current production and potential production, and develop different estimates of potential production, without involving actual volumes of water as input. Data employed in this study relies only on the accuracy of classifying agricultural lands by irrigation source, or the distribution of access and use of irrigation sources, and not the additional uncertainty associated with monitoring water volumes used from these sources. Estimates on volumes of water used are often also included in agricultural censuses, but are prone to poor or limited monitoring.

Conclusion

Irrigation is dynamically related to India's agricultural economy and environment. It is thus essential to understand the current contribution of surface water and groundwater to current agricultural production in order to protect against the accelerated depletion of groundwater resources. We quantified the contribution of surface water and groundwater to the current and potential production of rice and wheat grains in India as follows:

1) Groundwater currently irrigates a larger percentage of lands sown for both rice and wheat than surface water. Surface water currently irrigates 25 and 27 % of land sown with rice and wheat, respectively, while groundwater irrigates 35 and 66 %, respectively (Table 4, Fig. 9, 10).

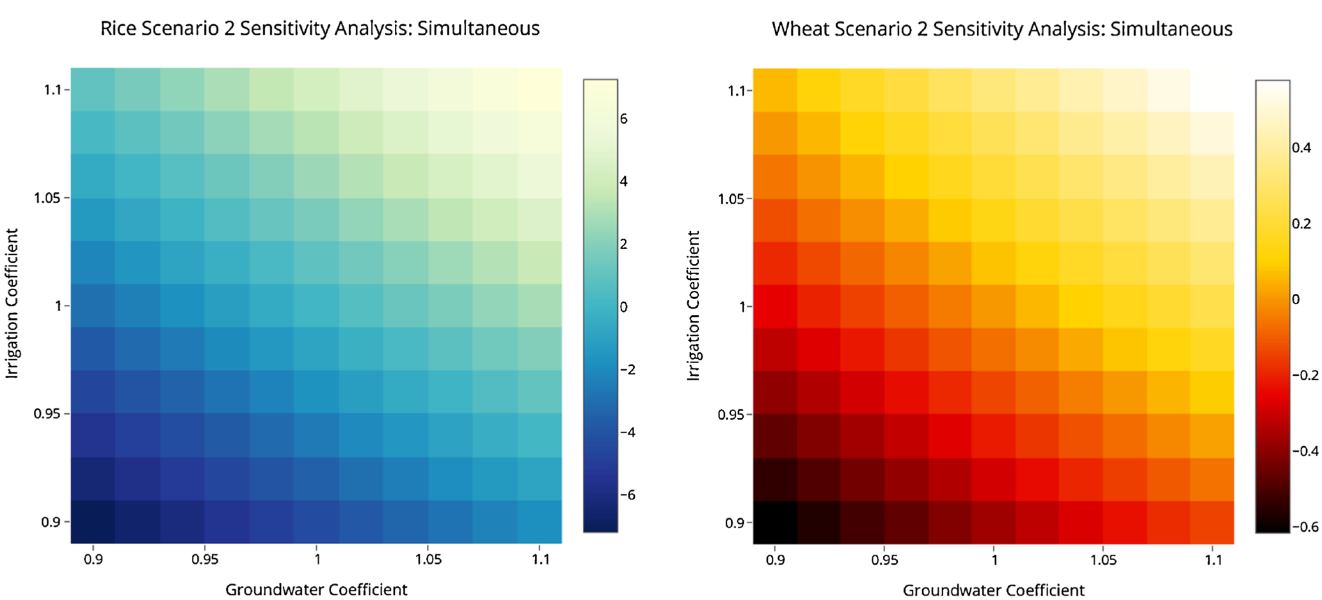


Fig. 12 Sensitivity analysis for scenario 2, simultaneously varying the irrigation and groundwater coefficients. The *y-axis* represents the irrigation coefficient, and the *x-axis* represents the groundwater coefficient, both vary by up to 10 %. The colour of the associated coordinate represents the percent difference from the estimates provided in the article as per the legend. The *left square* represents rice, and the *right square* represents wheat

Table 9 Sensitivity Analysis for scenario 2, simultaneously changing both the irrigation and groundwater coefficient. Values are in percent and are the differences between the original estimates and estimates with the changed coefficient

	C_{GW} −10 %, C_I −10 %	C_{GW} −10 %, C_I +10 %	C_{GW} +10 %, C_I −10 %	C_{GW} +10 %, C_I +10 %
Rice	−7.2	0.9	−1.8	7.2
Wheat	−0.6	0.1	−0.2	0.6

2) Irrigating with groundwater often allows for both the tailoring of volumes of water and timing of application as compared to irrigating with surface water, and accordingly groundwater irrigation often results in higher grain production. Surface water irrigates 24 and 25 % of rice and wheat production, respectively while groundwater irrigates 49 and 72 %, respectively (Table 5, Fig. 10).
3) We estimate that without irrigation, a significant portion of rice and wheat grain production would be lost: rice production would be at 75 % of current production, and wheat at 51 %. However, this is an estimate under normal climatic conditions, and such losses would be significantly altered in years of increased climatic variability and uncertainty (Fig. 10).
4) Increasing rice and wheat grain production with irrigation is near its production potential: rice production is estimated to be between 80 and 88 % of its production potential, while wheat is estimated to be already at 97 %. Irrigating currently non-irrigated fields would provide a production increase of between 14 and 25 % for rice, and 3 % for wheat (Table 6, Fig. 10). However, to close such yield gaps a 67 % increase in gross area irrigated and 31 % increase in irrigation water consumption would be required for rice, and an 8 % increase in gross area irrigated and 3 % increase in irrigation water consumption for wheat.
5) The expansion of irrigation to increase agricultural production necessitates a disproportionate increase in the area equipped for irrigation and water consumption as compared to the estimated gains in production. With increasing competition for water resources and projections of increased climatic variability, initiatives towards increasing production and food security without increasing stress on water resources, such as supplementary irrigation, may be more appropriate than the expansion of irrigation.

The methods developed in this paper provide estimates of potential yield and subsequent potential production in a manner tailored to the current irrigation and management practices within each of India's States and Union territories as compared to previous analyses. Such methods also allow for the recognition of hotspots and ranking of States for production potential, providing a framework for decision making with respect to future investments in irrigation and technology. Our methods can easily be adapted to other regions and crops, with the data required generally available in a nation or sub-nation's agricultural census. To create a sustainable and resilient agricultural economy in India, it is essential that policymakers, governing agencies, and community collectives understand the current contribution of different irrigation sources to agricultural production.

Acknowledgments The data for this paper were compiled from www.indiastat.com, and compilations and calculations are freely available from the authors upon request.

References

Briscoe, J., & Malik, R. (2006). *India's water economy: Bracing for a turbulent future*. New Delhi: Oxford University Press.

Burke, J. (2002). Groundwater for irrigation: productivity gains and the need to manage hydro-environmental risk. *Intensive use of groundwater: Challenges and opportunities*, 59–91.

Central Ground Water Board. (2011). *Dynamic ground water resources of India*. Faridabad: Central Ground Water Board, Ministry of Water Resources, Government of India.

Cheema, M., Immerzeel, W., & Bastiaanssen, W. (2014). Spatial quantification of groundwater abstraction in the Irrigated Indus Basin. *Groundwater, 52*(1), 25–36.

Custodio, E., & Llamas, M. (2003). Intensive use of groundwater: introductory considerations. *Intensive use of groundwater: Challenges and opportunities*, 3–12.

de Fraiture, C., Wichelns, D., Rockström, J., Kemp-Benedict, E., Eriyagama, N., Gordon, L. J., et al. (2007). Looking ahead to 2050: scenarios of alternative investment approaches. In D. Molden (Ed.), *Water for food, water for life* (Vol. Comprehensive assessment of water management in agriculture). London and Columbo: Earthscan and International Water Management Institute.

Dhawan, B. (1995). *Groundwater depletion, land degradation, and irrigated agriculture in India*. New Delhi.

Fishman, R. M., Siegfried, T., Raj, P., Modi, V., & Lall, U. (2011). Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation. *Water Resources Research, 47*(6).

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., et al. (2011). Solutions for a cultivated planet. *Nature, 478*(7369), 337–342.

Food and Agriculture Organization of the United Nations. (2009). *Eradicating hunger and pushing economic and social growth*. Rome: FAO.

Gandhi, V. P., & Bhamoriya, V. (2011). Groundwater Irrigation in India. *India Infrastructure Report*, 90.

Garduño, H., Romani, S., Sengupta, B., Tuinhof, A., & Davis, R. (2011). India groundwater governance case study. doi:© World Bank. https://23.21.67.251/handle/10986/17242 License: CC BY 3.0 IGO.

Giordano, M. (2006). Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: a first-cut assessment. *Hydrogeology Journal, 14*(3), 310–318.

Giordano, M., & Villholth, K. G. (2007). (Vol. 3): CABI.

Gleeson, T., & Wada, Y. (2013). Assessing regional groundwater stress for nations using multiple data sources with the groundwater footprint. *Environmental Research Letters, 8*(4), 044010.

Gleeson, T., Wada, Y., Bierkens, M. F., & van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature, 488*(7410), 197–200.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science, 327*(5967), 812–818.

Government of India (2011). Minor irrigation. http://www.archive.india.gov.in/sectors/water_resources/index.php?id=13. Accessed 19/05/2014.

Hernandez-Mora, N., Llamas, R., & Cortina, L. M. (2001). Misconceptions in Aquifer Over-Exploitation: Implications for Water Policy in Southern Europe. In *Agricultural use of groundwater* (pp. 107–126): Springer.

Jain, S. K., Agarwal, P. K., & Singh, V. P. (2007). Hydrology and water resources of India-Volume 57 of Water science and technology library-Tributaries of Yamuna river. Springer, 350pp.

Janakarajan, S., & Moench, M. (2006). Are wells a potential threat to farmers' well-being? Case of deteriorating groundwater irrigation in Tamil Nadu. *Economic and Political Weekly, 41*(37), 3977–3987.

Kahnert, F., & Levine, G. (1993). *Groundwater irrigation and the rural poor: Options for development in the gangetic basin:[papers were presented at the World Bank colloquium on groundwater irrigation, held April 12–14, 1989]*. Washington: The World Bank.

Konikow, L. F. (2011). Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters, 38*(17).

Kumar, M. D., Sivamohan, M., & Narayanamoorthy, A. (2012). The food security challenge of the food-land-water nexus in India. *Food Security, 4*(4), 539–556.

Licker, R., Johnston, M., Foley, J. A., Barford, C., Kucharik, C. J., Monfreda, C., et al. (2010). Mind the gap: how do climate and agricultural management explain the 'yield gap'of croplands around the world? *Global Ecology and Biogeography, 19*(6), 769–782.

Llamas, R., & Custodio, E. (2003). Intensive use of groundwater: a new situation which demands proactive action. *Intensive use of groundwater: Challenges and opportunities* (13–31).

Lowdermilk, M. K., Early, A. C., & Freeman, D. M. (1978). *Farm irrigation constraints and farmers' responses: Comprehensive field survey in Pakistan*. Fort Collins: Water Management Research Project, Engineering Research Center, Colorado State University.

Lundqvist, J., de Fraiture, C., & Molden, D. (2008). Saving water: from field to fork. Curbing losses and wastage in the food chain.

Mall, R., Gupta, A., Singh, R., Singh, R., & Rathore, L. (2006). Water resources and climate change: an Indian perspective. *Current Science, 90*(12), 1610–1626.

Meenakshi, J., Banerji, A., Mukherji, A., & Gupta, A. (2012). Impact of metering of tube wells on groundwater use in West Bengal, India.

Ministry of Agriculture (2001). Water requirement of crop in India. http://www.indiastat.com/table/agriculture/2/irrigation/145/7450/data.aspx. Accessed 19/05/2014.

Ministry of Agriculture (2011). State-wise distribution of number of operational holdings and area operated for all social groups in India (2010–2011). http://www.indiastat.com/table/agriculture/2/agriculturallandholdings20102011/718835/719086/data.aspx. Accessed 19/05/2014.

Ministry of Water Resources (2001a). 3rd census of minor irrigation schemes (2000–01): National level reports http://mowr.gov.in/micensus/mi3census/nt_level.htm. Accessed 19/05/2014.

Ministry of Water Resources (2001b). Reports ON 3rd Census of minor irrigation schemes (2000–2001). Accessed 19/05/2014.

Molden, D., Frenken, K., Barker, R., Fraiture, C. D., Mati, B., Svendsen, M., et al. (2007). Trends in water and agricultural development. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 57–89). London: Earthscan.

Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles, 22*(1).

Mukherji, A. (2006). Political ecology of groundwater: the contrasting case of water-abundant West Bengal and water-scarce Gujarat, India. *Hydrogeology Journal, 14*(3), 392–406.

Mukherji, A. (2012). Rural electrification for a second green revolution in West Bengal [India]. *IWMI-Tata Program and Water Policy Highlights*.

Mukherji, A., Shah, T., & Banerjee, P. (2012a). Kick-starting a second green revolution in Bengal [India]. *IWMI-Tata Program and Water Policy Highlights*.

Mukherji, A., Shah, T., & Giordano, M. (2012b). Managing energy-irrigation nexus in India: a typology of state interventions.

Nair, N., & Shah, T. (2012). The other side of India's electricity-groundwater nexus: the disruptive impact of tube well irrigation on rural development in western India. *IWMI-Tata Program and Water Policy Highlights*.

Portmann, F. T., Siebert, S., & Döll, P. (2010). MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. *Global biogeochemical cycles, 24*(GB1011), doi:10.1029/2008GB003435.

Ribot, J. C., Magalhães, A. R., & Panagides, S. (1996). *Climate variability, climate change and social vulnerability in the semi-arid tropics*. Cambridge: Cambridge University Press.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472–475.

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature, 460*(7258), 999–1002.

Seckler, D. W. (1998). *World water demand and supply, 1990 to 2025: Scenarios and issues* (Vol. 19). Colombo: International Irrigation Management Institute (IIMI); IWMI.

Shah, T. (1993). *Groundwater markets and irrigation development*. Oxford: Oxford University Press.

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters, 4*(3), 035005.

Shah, T. (2010). *Taming the anarchy: Groundwater governance in South Asia*. Washington: Resources for the Future.

Shah, T., Molden, D., Sakthivadivel, R., & Seckler, D. (2000). *Groundwater: Overview of opportunities and challenges*. Colombo: IWMI.

Shah, T., Roy, A. D., Qureshi, A. S., & Wang, J. Sustaining Asia's groundwater boom: An overview of issues and evidence. In

Natural Resources Forum, 2003 (Vol. 27, pp. 130–141, Vol. 2): Wiley Online Library

Shah, T., Burke, J., Villholth, K., Angelica, M., Custodio, E., Daibes, F., et al. (2007). Groundwater: A global assessment of scale and significance. In D. Molden (Ed.), *Water for food, water for life: A comprehensive assessment of water management in agriculture* (pp. 395–423). London: Earthscan.

Shah, T., Bhatt, S., Shah, R., & Talati, J. (2008). Groundwater governance through electricity supply management: assessing an innovative intervention in Gujarat, western India. *Agricultural Water Management, 95*(11), 1233–1242.

Shiva, V. (1991). The green revolution in the Punjab. *The Ecologist, 21*(2), 57–60.

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*(3), 198–217.

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., et al. (2010). Groundwater use for irrigation–a global inventory. *Hydrology and Earth System Sciences, 14*, 1863–1880. doi:10.5194/hess-14-1863-2010.

Siebert, S., Henrich, V., Frenken, K., & Burke, J. (2013). *Update of the digital Global Map of Irrigation Areas (GMIA) to Version 5*. Germany: Institute of Crop Science and Resource Conservation, Rheinische Friedrich-Wilhelms-Universität Bonn.

Singh, D. (2003). Groundwater Markets and Institutional Mechanism in Fragile. *Water resources, sustainable livelihoods, and eco-system services*, 311.

Thenkabail, P. S., Biradar, C. M., Noojipady, P., Dheeravath, V., Li, Y., Velpuri, M., et al. (2009). Global irrigated area map (GIAM), derived from remote sensing, for the end of the last millennium. *International Journal of Remote Sensing, 30*(14), 3679–3733.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature, 418*(6898), 671–677.

Tiwari, V., Wahr, J., & Swenson, S. (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters, 36*(18).

United Nations, D. o. E. a. S. A., Population Division (2013). World population prospects: The 2012 revision,

Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science, 289*(5477), 284–288.

Wada, Y., van Beek, L. P., van Kempen, C. M., Reckman, J. W., Vasak, S., & Bierkens, M. F. (2010). Global depletion of groundwater resources. *Geophysical Research Letters, 37*(20).

Wada, Y., Beek, L. P., Sperna Weiland, F. C., Chao, B. F., Wu, Y.-H., & Bierkens, M. F. (2012). Past and future contribution of global groundwater depletion to sea-level rise. *Geophysical Research Letters, 39*(9).

World Bank (2001). India : Power supply to agriculture, volume 1. Summary Report. Washington, DC.

World Bank (2010a). Deep wells and prudence : Towards pragmatic action for addressing groundwater overexploitation in India. doi:© World Bank. https://openknowledge.worldbank.org/handle/10986/2835 License: Creative Commons Attribution CC BY 3.0.

World Bank (2010b). Managing land and water to feed nine billion people and protect natural systems. In *World Development Report 2010* (pp. 133–187).

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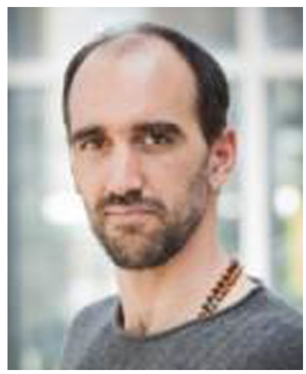

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