AGRICULTURE

# Alternative cereals can improve water use and nutrient supply in India



**Kyle Frankel Davis[1,2]*, Davide Danilo Chiarelli[3], Maria Cristina Rulli[3], Ashwini Chhatre[4], Brian Richter[5], Deepti Singh[6,7], Ruth DeFries[8]**

**Humanity faces the grand challenge of feeding a growing, more affluent population in the coming decades while reducing the environmental burden of agriculture. Approaches that integrate food security and environmental goals offer promise for achieving a more sustainable global food system, yet little work has been done to link potential solutions with agricultural policies. Taking the case of cereal production in India, we use a process-based crop water model and government data on food production and nutrient content to assess the implications of various crop-shifting scenarios on consumptive water demand and nutrient production. We find that historical growth in wheat production during the rabi (non-monsoon) season has been the main driver of the country's increased consumptive irrigation water demand and that rice is the least water-efficient cereal for the production of key nutrients, especially for iron, zinc, and fiber. By replacing rice areas in each district with the alternative cereal (maize, finger millet, pearl millet, or sorghum) with the lowest irrigation (blue) water footprint (WFP), we show that it is possible to reduce irrigation water demand by 33% and improve the production of protein (+1%), iron (+27%), and zinc (+13%) with only a modest reduction in calories. Replacing rice areas with the lowest total (rainfall + irrigation) WFP alternative cereal or the cereal with the highest nutritional yield (metric tons of protein per hectare or kilograms of iron per hectare) yielded similar benefits. By adopting a similar multidimensional framework, India and other nations can identify food security solutions that can achieve multiple sustainability goals simultaneously.**



## INTRODUCTION

Global crop production has more than tripled since the 1960s, leading to increased food supply per capita, lower food prices, and reduced malnutrition worldwide (*1*). This remarkable growth in global food supply has been accompanied by the depletion of freshwater resources for irrigation (*2*–*4*), nutrient pollution from injudicious fertilizer application (*5*, *6*), and rising greenhouse gas emissions (*7*, *8*). There is therefore widespread agreement that agriculture's use of planetary systems is unsustainable (*9*–*13*) and that humanity will need to feed an additional 2 billion people by 2050 while also minimizing the environmental consequences of the global food system (*1*, *14*). Numerous studies have explored strategies to resolve this food-environment dilemma [for example, (*1*, *7*, *11*, *13*, *14*)], but little work has been done to examine nutritional and environmental outcomes together or to identify concrete policy pathways by which these solutions may be put into action within specific countries. Given the immediacy of food security and sustainability challenges around the world, incorporating these solutions by leveraging a nation's existing agricultural policies offers promise to better link science with real-world outcomes.

The need for improved compatibility between food security and environmental stewardship is of considerable urgency in India. The world's second most populous country, India, has remained largely self-sufficient in terms of cereal production over the past 50 years, with rice (grown during the kharif/monsoon season) and wheat (grown during the rabi/winter season) as the flagship crops driving substantial increases in food supply (*15*). While the boom in rice-wheat systems has vitally contributed to reducing hunger and malnutrition throughout India (*16*), these trends in production have been supported by ever-increasing agricultural inputs and extensive environmental consequences, particularly for freshwater resources. Many parts of the country now experience chronic water stress due to heavy-water extraction for irrigated agriculture (*17*–*19*) and a weakening monsoon (*20*–*22*), while widespread nutrient deficiencies persist (*23*, *24*). Because Indian diets generally derive a large fraction of nutrients from cereals (*25*), these mounting food security and environmental challenges make it increasingly clear that the rice-wheat status quo of the Indian food system requires critical examination and that solutions that integrate nutrition and the environmental impacts of food production can offer pathways toward healthier food baskets with less environmental burden (*26*).

Because India relies mainly on domestic production, the country presents an excellent opportunity for examining how alterations of production within the country could potentially benefit nutrition and water use. Recent work [for example, (*27*, *28*)] has demonstrated the large inefficiencies present in food systems in terms of water use, showing the possibility of planting crops with lower water requirements while also enhancing calorie and protein production. Other studies in central India have examined water stress, land use, nutrition, and climate sensitivity associated with cereal production and demonstrated that certain cereals can offer distinct benefits over rice along all of these dimensions (*19*, *29*, *30*). However, a national analysis of the potential nutritional and water use benefits of alternative cereals (that is, maize, millets, and sorghum) is still lacking for India.

To do this, we first examine how Indian cereal production has changed through time, what this has meant for historical water use and nutrient production, and how these dimensions might benefit from alternative mixes of cereal crops. We limit our analysis to consider four key nutrients—calories, protein, iron, and zinc—for which cereals serve as the major source in Indian diets (*25*). For each district, we first quantify the water requirements [equal to the evapotranspiration from a crop over a growing season; units are in millimeters of $H_2O$ per year

[1]The Earth Institute, Columbia University, New York, NY 10025, USA. [2]The Nature Conservancy, New York, NY 10001, USA. [3]Department of Civil and Environment Engineering, Politecnico di Milano, Milan, Italy. [4]Indian School of Business, Hyderabad, India. [5]Sustainable Waters, Crozet, VA 22932, USA. [6]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA. [7]School of the Environment, Washington State University, Vancouver, WA 99164, USA. [8]Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY 10027, USA.
*Corresponding author. Email: kd2620@columbia.edu

(hereinafter mm $H_2O$ year$^{-1}$)] for each of the major cereal crops grown in India [rice (*Oryza sativa*), maize (*Zea mays*), wheat (*Triticum aestivum*), sorghum (jowar; *Sorghum vulgare*), pearl millet (bajra; *Pennisetum typhoideum*), and finger millet (ragi; *Eleusine coracana*)], using average climate data for 2000 through 2009 and categorizing based on growing season (kharif/monsoon for rice, maize, finger millet, and pearl millet; rabi/winter for wheat; and both seasons for sorghum). We then combine this information with historical production data (*31*) to estimate crop demand—the product of crop water requirement (CWR) and harvested area—for green water (that is, rainfall) and blue water (that is, irrigation required to avoid crop water stress) from 1966 through 2009. We also assess patterns of reliance on irrigation and water stress to examine how they have shifted with increasing cereal production.

We then use this information to evaluate several replacement scenarios in which rice areas in each district are instead planted with alternative kharif cereals and, in doing so, we seek to examine whether food security goals and improvements in freshwater use can be achieved in tandem. These scenarios are motivated by two key objectives of the Indian government, namely, to alleviate undernourishment by increasing the supply of nutritious foods (*32*) and to promote sustainable water resource management in agriculture (*33*). Specifically, we consider four primary district-level scenarios aligning with these objectives by replacing rice-harvested areas with (i) the lowest total water footprint (WFP) crop, (ii) the lowest blue WFP crop, (iii) the crop with the highest nutritional yield in terms of protein, and (iv) the crop with the highest nutritional yield in terms of iron and quantify what the changes in water use and nutrient production would be. Finally, we examine an important potential policy lever—India's Public Distribution System (PDS)—by which these transitions toward alternative cereal production and consumption could be realized. In doing all of this, we can determine where and to what extent efforts to promote alternative mixes of cereals—for which there is local knowledge regarding cultivation and consumption—could simultaneously improve water use efficiency and nutrient availability in diets.

## RESULTS

CWRs showed substantial variation both between crops and geographically (units are in mm $H_2O$ year$^{-1}$; Table 1, figs. S1 and S2, and table S1). As expected, we found that the highest total CWRs occurred for rice and wheat and that demand for irrigation was more pronounced in arid regions (for example, Rajasthan and Maharashtra; figs. S2 and S3). We also observed high blue (irrigation) water requirements for all rabi (non-monsoon, winter) crops as they must rely more heavily on irrigation (Fig. 1).

**Table 1. National average CWRs weighted by district production.** CWRs (mm $H_2O$ year$^{-1}$) were calculated for each district using averaged climate variables covering the years 2000 through 2009. Green CWRs for rainfed crops are consistently higher than for irrigated crops because of differences in the distribution of rainfed (R) and irrigated (I) cereal production. Values in parentheses are the production-weighted SDs. Ellipses indicate that the crop is not produced during a particular season.

| Crop | Kharif | | | Rabi | | |
|---|---|---|---|---|---|---|
| | Green (R) | Green (I) | Blue (I) | Green (R) | Green (I) | Blue (I) |
| Rice | 641 (160) | 570 (157) | 307 (126) | 263 (47) | 189 (52) | 622 (162) |
| Wheat | … | … | … | 321 (57) | 272 (50) | 517 (91) |
| Maize | 439 (48) | 415 (45) | 49 (47) | 259 (38) | 181 (36) | 237 (46) |
| Sorghum | 425 (59) | 400 (56) | 44 (42) | 220 (72) | 146 (54) | 179 (42) |
| Finger millet | 424 (39) | 400 (30) | 59 (78) | … | … | … |
| Pearl millet | 314 (129) | 296 (119) | 46 (60) | … | … | … |

Cereal production has grown by 230% from 1966 to 2009. Although the combined production of alternative cereals (that is, those other than rice and wheat) was larger than that of wheat in the 1960s, their relative contribution to the cereal supply has steadily dwindled (fig. S4, A and B). Yet, alternative cereals still disproportionately account for the supply of protein, iron, and zinc among kharif crops (table S2 and fig. S5). At the same time, total consumptive water demand for Indian cereal production has increased from 482 to 632 km$^3$ $H_2O$ year$^{-1}$ during the study period; this increase has been driven almost entirely by a doubling of consumptive blue water demand for wheat during the rabi season (Fig. 1) and modest increases in cropping frequencies and cropland extent (fig. S4, C and D). Not surprisingly, the largest increases in consumptive water demand occurred in the states of Punjab and Haryana, where irrigated rice and wheat production now occurs at commercial scales. The continuing transition to rice- and wheat-dominated croplands has also increased the proportion of crop water demand met through irrigation, especially in the country's northern states (Fig. 2, A to D). When comparing consumptive water demand to long-term average renewable water availability (that is, water generated from annual precipitation), we also observed that many districts were already experiencing substantial water stress at the beginning of the time period and that the burden of water stress has shifted away from southern districts, some of which have experienced a decrease in crop water demand, and toward districts located largely in Punjab and Haryana (Fig. 2, E and F).

We also examined the water productivities [that is, WFP; cubic meters of $H_2O$ consumed per ton of crop produced (hereinafter, m$^3$ $H_2O$ ton$^{-1}$)] of the different cereals for the production of key nutrients. When using the conventional metric of WFP, we found that rice (1490 m$^3$ $H_2O$ ton$^{-1}$) was by far the most inefficient blue water user among the kharif (monsoon) crops and that the total WFP of sorghum grown during the rabi season was nearly double that of wheat (Fig. 3). In addition, rice was the least productive water user among monsoon cereals when examining nutrient production, rivaling rabi (winter)

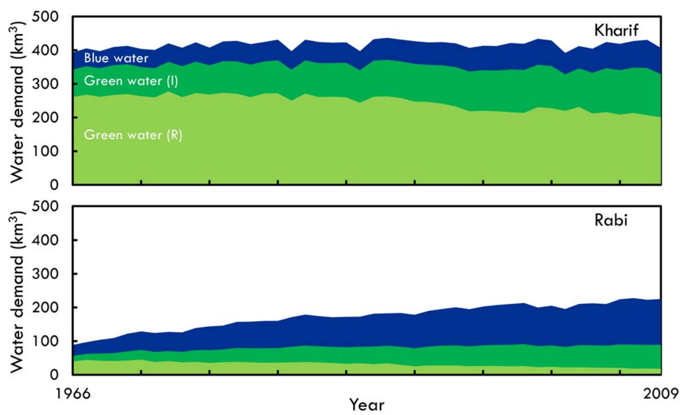


**Fig. 1. Time series of consumptive water demand for Indian cereal production.** Consumption is disaggregated between precipitation on rainfed lands [Green water (R)], precipitation on irrigated lands [Green water (I)], and irrigation water on irrigated lands (Blue water).

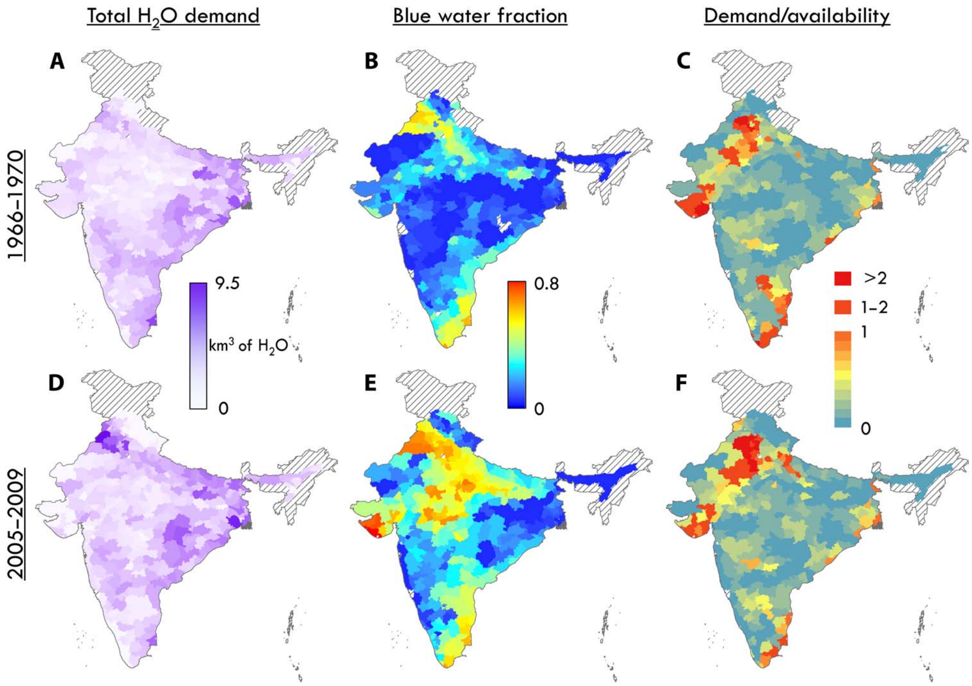


**Fig. 2. District-level changes in total consumptive water demand for cereal production, blue water fraction, and water stress.** Total consumptive water demand for cereal production is compared for the beginning of the study period [(**A**) 1966–1970] and the end of the study period [(**D**) 2005–2009]. (**B** and **E**) Blue water fractions for the beginning and end of the study period are the ratio of consumptive blue water use to total consumptive water use for cereal production. "Availability" is the long-term (1970–2000) average of available renewable water, which originates from annual precipitation and contributes to stream flow and groundwater recharge. (**C** and **F**) If the ratio of consumptive water demand to annual availability exceeds unity, then the difference must be met through nonrenewable sources and can lead to the depletion of freshwater resources (for example, through groundwater pumping).

crops in the volume of blue water required per ton of calories, protein, and zinc production and surpassing all crops for water requirements for iron production. Maize consistently performed well across all nutrient metrics, particularly with regard to irrigation water productivity. Together with the inefficiencies of rice, these results indicate that greater incorporation of alternative cereals into the Indian food system can offer considerable potential benefits in terms of nutrition and water use, although it is important to note that, due to relatively low yields, sorghum, pearl millet, and finger millet showed potential trade-offs between water productivity and land use efficiency. Combined with the differing geographies and climates that these cereals currently occupy (fig. S1), these considerations necessitated comparisons at finer scales as the relative ranking of crops can vary widely between districts (fig. S6).

With these potential trade-offs between water, land, and nutrition in mind, we considered multiple district-level rice replacement scenarios aimed at reducing consumptive water demand for kharif (monsoon) cereal production, improving nutrient production from cereals, and conserving the extent of cultivated land, all of which are goals of the Indian government. We first replaced rice areas with the kharif cereal having the lowest total WFP in each respective district, provided that the replacing crop had a total WFP ($m^3$ $H_2O$ $ton^{-1}$) lower than rice (Fig. 4, A and E), and found that, in doing so, it is possible for India to substantially reduce consumptive water demand (−21% for green water and −32% for blue water; fig. S7); increase protein (+9%), iron (+43%), and zinc (+28%) supply; and maintain calorie (+1%) production (Fig. 4I). Much of these benefits for water and nutrition came from relatively few districts, with half of total water savings for this scenario coming from just 39 districts (table S3). The districts that stood to benefit the most in terms of reduced water demand were also those largely responsible for increases in nutrient production. This additional nutritional supply from this scenario could serve to address persistent deficiencies, particularly for iron (table S4) (*23*, *25*), and could help to compensate for insufficient nutrient supply from other food groups of the Indian diet. Performing replacements based on blue WFPs yielded similar results, although with a modest reduction in calorie supply (scenario 2; Fig. 5A and table S4). For both of these scenarios, we found that nutrient production would be more evenly distributed across the country (as opposed to being concentrated in Punjab and Haryana) and that the largest increases in nutrient production generally occurred in eastern India (fig. S8).

We also considered two scenarios in which rice was replaced by the alternative kharif cereal with the highest nutrition yield—in terms of either protein or iron—within each district (Fig. 4 and table S4). Both scenarios yielded similar results to the minimum WFP scenarios, with substantial improvements in water use and in protein, iron, and zinc production but with mixed outcomes for calorie supply (maximum protein, +8.7%; maximum iron, −4.5%; Fig. 4I). Overall, the benefits of rice replacement across all scenarios were more pronounced within rainfed croplands and were largely attributable to relatively few districts (Fig. 5 and table S3). The modest calorie reductions that occurred in two of the four replacement scenarios were largely because the yields of alternative cereals were on average lower than those for rice (fig. S9 and table S7). However, it is important to note that, of the 296 districts where rice is cultivated, there are many instances where alternative cereals achieve higher yields relative to rice (8 for finger millet, 139 for maize, 36 for pearl millet, and 55 for sorghum). In all, there are 149 districts where at least one of the alternative cereals considered here attained a higher yield than rice (table S6). The high yields and low CWRs of maize relative to the other alternative cereals made it the

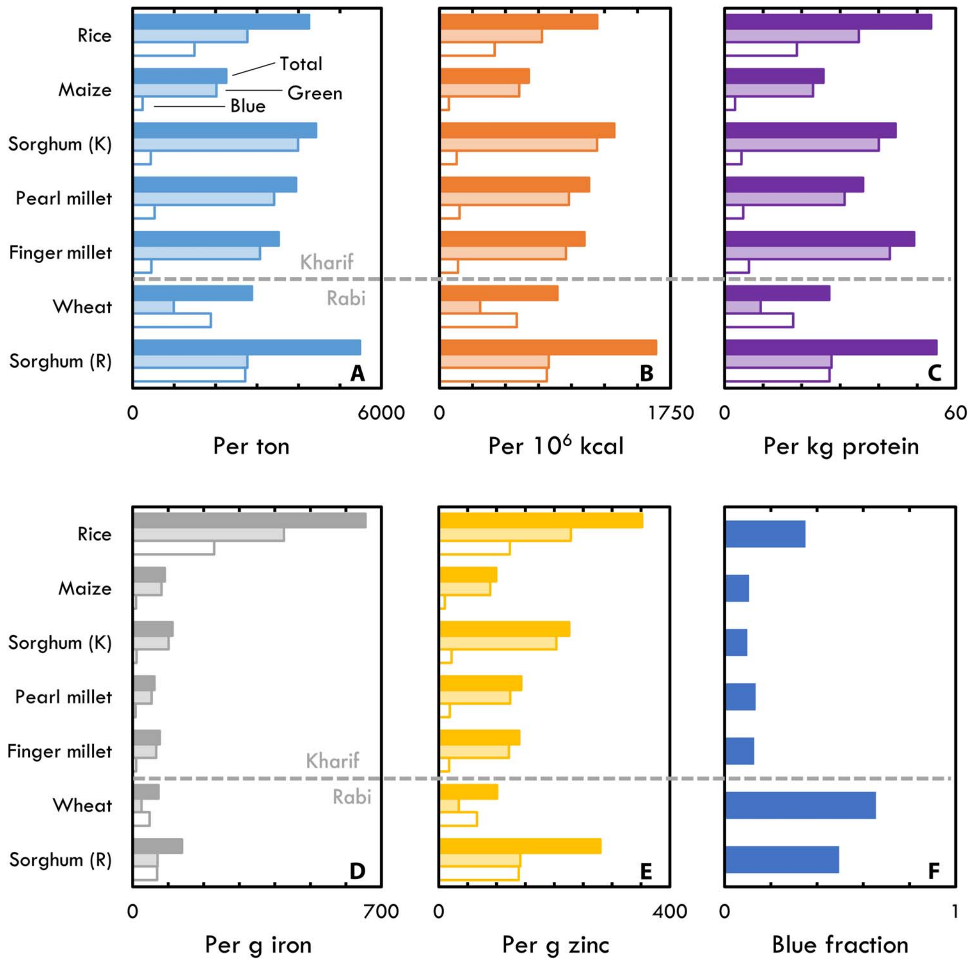


**Fig. 3. Water productivity ($m^3$ $H_2O$) of nutrient production for total, blue, and green WFPs.** Values correspond to the years 2000 through 2009 and represent the ratio of conventional WFPs on irrigated cropland [(**A**) that is, $m^3$ $H_2O$ $ton^{-1}$] to nutrient content (that is, amount of nutrient per ton of crop) for (**B**) calories, (**C**) protein, (**D**) iron, and (**E**) zinc. Blue fraction (**F**) is the ratio of blue WFP to total WFP.

dominant replacement crop in two of the four scenarios (scenario 1: lowest total WFP; scenario 3: highest protein yield; Fig. 4 and table S4). In many parts of the country, maize is not traditionally consumed to the same extent as millets and sorghum, and cultural preferences will strongly determine the realistic possibilities for alternative cereals, which may differ in certain places from those selected by some of our scenarios. In view of this, we also imposed additional constraints on the replacement scenarios (that is, nutritional yield of replacing crop in terms of calories must be higher than rice and/or maize could not be considered as a replacement) and generally observed the same benefits of replacement, though of a smaller magnitude. In a few cases, trade-offs began to emerge between water savings and nutrient supply at the national level, highlighting the need for selective, well-considered, and location-specific strategies to promote alternative cereals (table S4).

As a final note, information on actual irrigation water withdrawals in India beyond country-level estimates is not available (*34*). As such, our study examines blue water demand and potential blue water savings, an approach that is widely used to compare the water use intensities of different crops and to provide insights into less water-demanding cropping choices (*3*, *18*, *28*, *35*–*38*). Depending on pumping capacity and irrigation source for an irrigated field, a farmer's actual irrigation availability may fall below a crop's irrigation water requirement (that is, the volume of irrigation water required to prevent crop water stress) and would mean that a crop shift may in reality realize lower or no blue water savings. However, in many cases, a transition to a crop that requires less irrigation water will not only result in real water savings but also leave a farmer's crops less exposed to potential water stress.

## DISCUSSION

A substantial increase in rice-wheat cropping, a system that depends heavily on irrigation, has contributed to chronic water stress in many parts of India (Fig. 2). There is widespread consensus (*17*, *39*–*41*) that these current practices, in combination with weakening monsoonal rains (*20*, *22*), offer little possibility of long-term sustainability for water use if India intends to continue to meet its cereal demand domestically. Even for countries expecting little population growth in the coming decades, policies of food self-sufficiency can present substantial food-water trade-offs. For instance, a recent study of neighboring Sri Lanka showed that the country's freshwater resources will be insufficient to sustainably supply the irrigation water required to continue maintaining rice production above domestic demand (*42*). For a country such as India, which will need to feed a projected 394 million more people by 2050 (*43*), the potential for undesirable trade-offs between food security

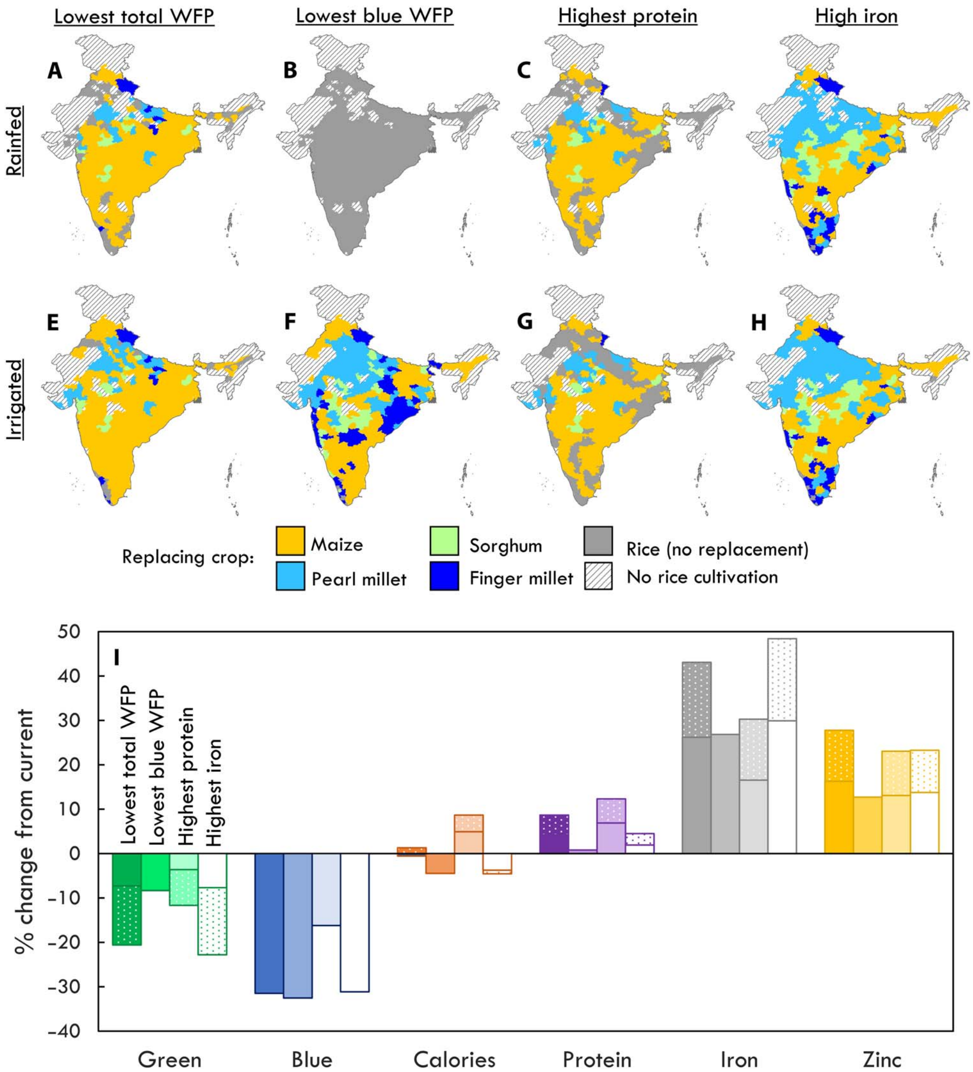


**Fig. 4. Outcomes of selected rice replacement scenarios.** Maps show the districts in which rice-harvested areas were replaced by kharif crop with (**A** and **E**) the lowest total WFP in each district (scenario 1), (**B** and **F**) the lowest blue WFP in each district (scenario 2), (**C** and **G**) the highest nutritional yield in terms of protein (metric tons of protein per hectare), and (**D** and **H**) the highest nutritional yield in terms of iron (kilograms of iron per hectare). (**I**) Solid columns correspond to irrigated areas, and patterned columns correspond to rainfed areas. Values are reported as percent changes relative to current levels of water demand and nutrient supply. Changes in water demand are separate between blue water (blue) and green water (green). Because we made no replacements in rainfed rice areas under the replacement scenario based on blue WFPs (scenario 2), there are no rainfed bars for this scenario. Current levels of water demand and nutrient production and the levels of minimum nutrient production required from cereals to meet daily recommended intake (DRI) for the country (if there were no limitations on access and distribution and no losses or waste) (*23*) are reported in tables S2 and S3.

and environmental sustainability is profound. Yet, our findings demonstrate that India can alleviate these difficult decisions by exercising flexibility in the types of cereals it produces and consumes.

Recent decades in India have shown that widespread changes in cereal mixes are possible within relatively short time periods. While there is still considerable consumption of alternative cereals in certain regions of the country (fig. S10), the continuing shift toward rice-wheat cropping and consumption indicates a substantial influence from the country's PDS (*44*), a program that leverages the country's tight linkages between food production and diets to promote food security for low-income households and livelihood support for smallholder farmers. By providing a guaranteed Minimum Support Price to producers and placing heavy subsidies on rice and wheat at the consumer end, this system has also served to influence cropping and dietary choices away from more nutrient-rich alternative cereals and is an important factor contributing to the persistence of widespread nutrient deficiencies (*25*, *44*).

By using similar policy mechanisms to transition to a greater reliance on other cereals, India can potentially realize important benefits in terms of both reduced consumptive irrigation water demand and increased production of key nutrients. Of course, there are multiple factors that dictate a farmer's crop choice and a household's consumption basket, and some of the reasons that producers and consumers may prefer rice and wheat may be difficult to influence. These considerations are essential for identifying where efforts aimed at increasing alternative grains may complement local priorities and preferences. With these very real challenges in mind, certain states (for example, Karnataka and Odisha) have initiated state-level pilot programs that will procure selected alternative cereals from farmers under their PDS programs. The removal of these

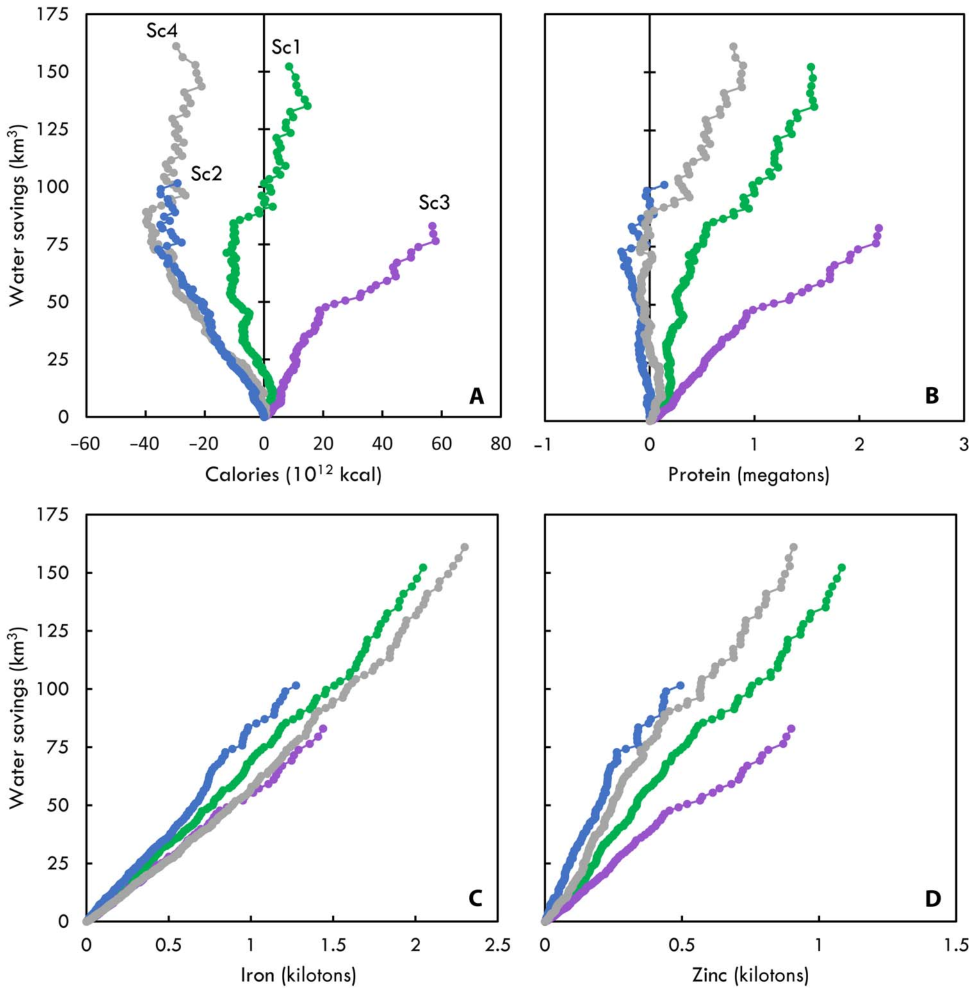


**Fig. 5. Cumulative water savings and changes in nutritional output.** For each rice replacement scenario (Sc1, Sc2, Sc3, and Sc4), districts were ranked based on volume of water savings from smallest to largest and plotted against their associated changes in the supply of (**A**) calories, (**B**) protein, (**C**) iron, and (**D**) zinc.

economic barriers (by which government procurement is only offered for rice and wheat) will therefore provide invaluable information on the willingness of farmers and households to increase alternative cereals in their production and consumption baskets.

It is clear that further work is needed to fully understand the suite of factors influencing cropping and dietary choices and their economic, nutritional, and environmental implications, and this study addresses important aspects of these knowledge gaps. We have shown that potential benefits of transitioning toward alternative cereals exist for both rainfed and irrigated systems, where substantial reductions in consumptive water demand are complemented by increased nutrient production (table S4). In addition, by improving water productivity for cereal production during the kharif (monsoon) growing season, more freshwater may be made available for rabi irrigation as well as for environmental flows and domestic, municipal, and industrial uses. Further, incorporation of alternative, less water-demanding cereals can help to increase crop diversity in Indian cereal production and reduce vulnerability to dry spells in places where freshwater resources for supplementary irrigation may be less readily accessible and can potentially enhance the resilience of the food system against future uncertainties associated with climate change [for example, (*30*)].

Our replacement scenarios also demonstrate that efforts at improving alternative cereal production can help to more equally distribute nutrient production across the country and thereby reduce the impact of a single local climate shock to national grain production. This decentralization of nutrient production—away from Punjab and Haryana—that these alternative cereals would afford would also represent a reversal of the trend in which cereal production (fig. S11) and water consumption have shifted away from southern states and served to enhance already existing water stress in the north (Fig. 2).

The potential food-water benefits demonstrated in this study were all realized while maintaining the current extent of cropland (that is, no agricultural expansion). Such a consideration is vital in a country with high population density and intensive pressure on land resources. Although we were able to constrain cultivated area, in certain cases, we found that important trade-offs exist between efficient land and water use for nutrient production (fig. S9) and that the magnitude of potential benefits from rice replacement and the choice of alternative crop varied widely between districts (fig. S6B and Fig. 4). While all replacement scenarios generally realized benefits for water use and nutrient supply, even a slight reduction (as occurred in certain cases for calories) may not be an acceptable outcome for a country in which nutrient supply is generally inadequate. Thus, in a country such as India, where a high fraction of people continue to be undernourished, policy-makers may seek to selectively encourage the production and consumption of alternative cereals only where these undesirable trade-offs will not occur. In the near term, efforts at altering the mix of cereal production should focus on those states in which farmers are already able to achieve relatively high yields for alternative cereals, thereby avoiding any undesirable outcomes for nutrient production, particularly for calories. Many of the trade-offs between nutrient supply and water use efficiency can be eliminated by focusing agricultural research on further improving yields of these alternative cereals and would almost certainly ensure greater improvements in nutrient production as well. Yet, even with these relatively low yields, maize, sorghum, pearl millet, and finger millet generally contributed to reductions in consumptive water demand and improvements in nutrient production under the rice replacement scenarios considered in this study (Fig. 5).

There are certainly a host of other considerations, beyond water and land use and nutrient production, that factor into agricultural policy and consumer choices, and the crops, environmental impacts, and nutrients included in such an analysis must be selected according to each situation. For Indian cereals in particular, there are several aspects of production and consumption that our analysis does not include but which are important for fully understanding the nutritional, economic, and environmental implications of shifting cropping patterns. As one example, rice residues serve as an important source of animal fodder, and animal products in turn provide key sources of protein and iron to the Indian population. There is a large body of literature showing that alternative cereals (and their residues) can readily be used as feed and fodder, that their nutritional qualities as feed and fodder exceed that of rice and rice residues, and that their use to support animal production already occurs across India [for example, (*45*–*52*)].

Further studies on dimensions such as greenhouse gas emissions and input costs, storage and transport costs, labor requirements, and dietary preferences are also required before any policy recommendations can responsibly be made. Studies that incorporate optimization approaches to develop trade-off frontiers can also help to reconcile these multiple objectives. While future work on these other factors is still needed, the cereals considered here offer great promise for improving water use and nutrient production while conserving agricultural extent. As such, the holistic approach that we have presented, in which multiple dimensions are considered in tandem, provides a mechanism for incorporating other economic and cultural dimensions into an integrated framework for sustainable decision-making. The outcome of this study demonstrates that nutrition and environmental outcomes need to be considered together, that existing policies can be used to achieve food-environment co-benefits in one of the world's most populous countries, and, more generally, that solutions for achieving sustainable intensification in any country are most effectively achieved if based on analyses of trade-offs and synergies across multiple dimensions.

## CONCLUSION

Nations are increasingly facing challenges of increasing food production while simultaneously minimizing resource use and environmental impacts. This is certainly the case for India where historical trends in cereal production have contributed to widespread water stress and nutrient deficiency. Our study demonstrates that replacing rice with other cereals, for which local knowledge on their production and consumption already exists, can offer distinct benefits in terms of both reducing freshwater use and enhancing nutrient production. This case study of India provides an example of how a multidimensional approach can be used in other places to assess sustainability goals at the interface of food security and the environment, to understand and avoid undesirable trade-offs, and to better link science with policy.

## MATERIALS AND METHODS

### Data

We examined the water use and nutrient content of rice (*O. sativa*), maize (*Z. mays*), wheat (*T. aestivum*), sorghum (jowar; *S. vulgare*), pearl millet (bajra; *P. typhoideum*), and finger millet (ragi; *E. coracana*), which constitute nearly all of India's cereal production (*15*). Data on district- and crop-specific production, harvested area, and irrigated area were taken from the International Crops Research Institute for the Semi-Arid Tropics Village Dynamics in South Asia (VDSA) mesoscale data set (*31*). These data are reported annually for the years 1966 through 2011 and use 1966 district boundaries. Data for the years 2010 and 2011 were incomplete and were not included in this study. While there has been substantial modification to district boundaries since 1966, the data provided in VDSA currently cover 593 of India's 707 districts and 87% of the country's land area. National values for nutrient content were taken from the newly released Indian Food Composition Tables (table S8) (*53*). Year 2011 district-level consumption data for each cereal came from the Indian National Sample Survey (table S6) (*24*). National DRI values for calories, protein, iron, and zinc came from India's National Institute of Nutrition (*23*).

Information on actual water withdrawals or pumping rates is not available for India, and estimations of CWRs provide the best alternative in examining the water needs of farmers across the country. CWRs were calculated for each district at monthly time steps for the years 2000 through 2009 and were split between "blue" and "green" CWRs, where green water is supplied through rainfall and blue water is supplied through irrigation (*2*). Blue water represents a crop's consumptive water demand in excess of what is provided through precipitation and is only used in calculations of consumptive water demand within irrigated areas. In reality, farmers with access to irrigation may not be able to fully meet the irrigation water demand of their crops, as limited by pumping rates and irrigation source. This means that, if a farmer pumped at maximum capacity but was still unable to obtain sufficient irrigation water to meet the blue water requirement of any of the crops considered here, the actual water use for the field would not change. For those farms where irrigation availability is only insufficient for the most water-intensive cereals, a shift to crops with lower water requirements will result in an actual reduction in irrigation water use. It is also clear that, if a farmer transitions to a crop with a lower blue water requirement, regardless of the irrigation water available to that field, this crop will be less exposed to conditions of water stress during dry years or drought.

Precipitation data came from the Indian Meteorological Department's daily rainfall product (1.0° × 1.0°) (*54*). Mean daily temperatures were taken from the University of East Anglia's Climate Research Unit Time Series version 3.24.01 data set (0.5° × 0.5°) (*55*). Monthly wind speed and relative humidity data came from the National Oceanic and Atmospheric Administration/Oceanic and Atmospheric Research/Earth System Research Laboratory Physical Sciences Division's National Centers for Environmental Prediction Reanalysis product (2.5° × 2.5°) (*56*). Soil information (sand, silt, and clay fractions) came from the International Soil Reference and Information Centre's 30–arc sec SoilGrids database (*57*). Data for net radiation at the surface (which also accounts for soil heat flux density) were taken from NASA's Global Land Data Assimilation System Noah Land Surface Model L4 monthly, Version 2.0 (0.25° × 0.25°) (*58*). Crop coefficients, climate zones, and growing stages were adapted from Mekonnen and Hoekstra (*35*) and Kottek *et al.* (*59*) (table S9 and fig. S12). State-level planting dates were determined by combining information from the Indian Meteorological Department (*60*), Portmann *et al.* (*61*), and Mekonnen and Hoekstra (*35*) (table S10). Growing stages for each district were shifted to align with both the crop coefficient values for the particular climate zone in which that district was located and the estimated planting date of that district's state. The same values for crop coefficients, growing stages, and planting dates were used for both pearl millet (bajra) and finger millet (ragi).

## Estimating atmospheric demands on crops

Reference evapotranspiration, $ET_o$, was calculated for each district at monthly time steps using the Food and Agriculture Organization of the United Nations' Penman-Monteith equation (*36*)

$$ET_{\mathrm{o}} = \frac{0.408\Delta(R_{\mathrm{n}} - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where $R_n$ is the net radiation at the crop surface (MJ $m^{-2}$ $day^{-1}$); $G$ is the soil heat flux density (MJ $m^{-2}$ $day^{-1}$); $T$ is the mean daily air temperature at 2 m (°C); $u_2$ is the wind speed at 2 m (m $s^{-1}$); $e_s$ and $e_a$ are the saturation and deficit vapor pressures, respectively (kPa); $\Delta$ is the slope vapor pressure curve (kPa°$C^{-1}$); and $\gamma$ is the pyschrometric constant (kPa°$C^{-1}$). The actual evapotranspiration ($ET_a$) of crop $i$ on day $t$ was then calculated as

$$ET_{a,i,t} = k_{c,i,t}k_{s,i,t}ET_{o,t} \quad (2)$$

where $k_{c,i,t}$ is the crop coefficient of crop $i$ corresponding to the month in which day $t$ occurs (table S9) and $k_{s,i,t}$ is the water stress coefficient calculated following Allen *et al.* (*36*) as a function of the soil water content in the root zone ($S_{i,t}$), the maximum and actual water content in the root zone. Rooting depths for irrigated and rainfed crops came from Siebert and Döll (*37*) (table S11). For crop $i$ on day $t$ under water-stressed conditions (that is, when only precipitation was provided), $k_{s,i,t}$ was evaluated as

$$k_{s,i,t} = \begin{cases} \dfrac{S_{i,t}}{(1-p_i)S_{\max,i}} & \text{if } S_{i,t} < (1-p_i)S_{\max,i} \\ 1 & \text{if } S_{i,t} \geq (1-p_i)S_{\max,i} \end{cases} \quad (3)$$

where $S_{i,t}$ is the depth-average soil moisture (expressed as a length), $S_{\max,i}$ is the value of available soil moisture, and $p_i$ is the fraction of $S_{\max,i}$ that a crop can uptake from the rooting zone as calculated in Allen *et al.* (*36*) and Siebert and Döll (*37*). For conditions of no water stress (where supplementary irrigation is available), $k_{s,i,t}$ was assumed to be 1 (*35*, *37*). For a given crop and grid cell, soil moisture ($S_{i,t}$) was calculated by solving a daily soil water balance

$$S_{i,t} = S_{i,t-1} + \Delta t(P_{\mathrm{eff},t} + I_{i,t} - ET_{a,i,t} - D_{i,t}) \quad (4)$$

where $S_{i,t-1}$ is the soil moisture of the previous time step, $\Delta t$ is equal to 1 day, $P_{\mathrm{eff},t}$ is the effective precipitation (that is, the rainfall that is actually absorbed in the soil and not directly evaporated from the surface), $I_{i,t}$ is the additional irrigation water (used only in the case of irrigated crops), and $D_{i,t}$ is deep percolation below the root zone (which occurred when soil moisture exceeded field capacity, that is, the volume of water that can be retained in the soil). Daily precipitation was converted to $P_{\mathrm{eff},t}$ using the Soil Conservation Service method [see, for example, (*35*, *36*, *62*)].

Thus, for each day, each crop, and each district, we were able to calculate a stressed $ET_{a,i,t,s}$ (equal to the green consumptive water use) and unstressed $ET_{a,i,t,u}$ (equal to the actual evapotranspiration under no water stressed). Blue consumptive water use was calculated as the difference between $ET_{a,i,t,s}$ and $ET_{a,i,t,u}$ and was only considered for irrigated areas. We then took a summation of the daily green and blue consumptive water use across a crop's entire growing season to determine total green (for rainfed and irrigated crops) and blue (for irrigated crops only) consumptive CWR, averaged across the years 2000 through 2009 (table S1). These definitions of green and blue consumptive water use are consistent with standard methodologies of WFP calculation [for example, (*35*)].

## Estimating historical consumptive water demand and water stress

Green consumptive water demand ($CWD_{green}$) for cereal production was estimated annually for each district $j$ as

$$\mathrm{CWD}_{\mathrm{green},j} = 10\sum(\mathrm{CWR}_{\mathrm{green},i,j}a_{i,j}) \quad (5)$$

where $CWR_{green,i,j}$ is the green CWR (mm $H_2O$ $year^{-1}$) of crop $i$, $a_{i,j}$ is rainfed area (ha) in district $j$ (calculated as the difference between harvested area and irrigated area), and the factor of 10 ensures that the units are in cubic meters of $H_2O$ per year. This calculation was repeated using the blue CWR and crop-specific irrigated area to determine the consumptive (blue) irrigation water demand. The irrigated area data from VDSA had some missing values, which we linearly interpolated. If data were missing at the beginning or end of the time period, then these values were linearly extrapolated based on the immediately succeeding or preceding 10 years, respectively. Complete data for crop-specific district-level irrigated area in West Bengal were only available for the years 1966, 1967, 1983, 1985, and 1988 from VDSA. To ensure that our estimates were conservative, we took the ratio of irrigated area to harvested area for each of these years, averaged these ratios across the 5 years of available data, and applied this constant irrigated/harvested ratio to all years. Because the VDSA crop production data set does not distinguish between kharif and rabi production for rice, maize, pearl millet, and finger millet, we used the CWRs for the kharif season for these crops to estimate total consumptive water demand. This assumption is supported by crop production data reported by season from the Directorate for Economics and Statistics (*63*), which shows that millet production during rabi is negligible and that only for selected states (for example, rice in Andhra Pradesh, Odisha, Tamil Nadu, and West Bengal, and maize in Andhra Pradesh, Bihar, Madhya Pradesh, and Tamil Nadu) is rabi production substantial for rice or maize. Wheat is exclusively produced during the rabi season with certain states producing small amounts of cereals outside of the kharif and rabi growing seasons.

Water stress was calculated as the ratio of total consumptive water demand for cereals to the long-term average renewable water availability for each district. Watershed-level data on renewable water availability (surface + groundwater) cover the years 1970 through 2000 and came from Brauman *et al.* (*4*) who used the WaterGAP3 integrated global water resources model. These data do not account for interbasin transfers or desalination. Brauman *et al.* (*4*) define available renewable water as "water generated [from precipitation] within the watershed and inflows from upstream that are stored or pass through rivers or move from the land surface into aquifers (renewable groundwater)." Using long-term average renewable availability allows for an examination of whether freshwater withdrawals and consumption can be sustained by a watershed through time. If consumptive water demand consistently exceeds the average renewable water available (and that is able to recharge annually), then the difference must be met through nonrenewable sources (for example, groundwater pumping) and can lead to the depletion of surface and groundwater sources.

### Replacing rice with alternative cereals

Rice replacement scenarios were based on the years 2000 through 2009 to align with the time period used for WFP calculations. Replacements were carried out separately for rainfed and irrigated croplands. Under all replacement scenarios, we assumed that the water resources available to rice fields would then become available to the replacing crop. To explore how increased production of alternative cereals may benefit outcomes for water demand and nutrient production, we examined four district-level scenarios by replacing rice in rainfed and irrigated areas with (i) the alternative cereal with the lowest total WFP, (ii) the alternative cereal with the lowest blue WFP, (iii) the alternative cereal with the highest nutritional yield in terms of protein (metric tons of protein per hectare), and (iv) the alternative cereal with the highest nutritional yield in terms of iron (kilograms of iron per hectare). For rainfed areas in scenario 1, green WFP was equal to total WFP. By replacing rice-harvested areas (instead of rice production), we were able to conserve agricultural extent and avoid any agricultural extensification. For scenario 1, the alternative cereal with the lowest total WFP in a given district replaced rainfed rice. If this crop had a total WFP higher than that of rice, then no replacement occurred for rainfed rice areas in that district. This scenario was applied separately to irrigated rice areas. For scenario 2, the alternative cereal with the lowest blue WFP in a given district replaced irrigated rice. If this crop had a blue WFP higher than that of rice, then no replacement occurred for irrigated rice areas in that district. This scenario was not applied to rainfed rice areas. For scenario 3 and scenario 4, the alternative cereal with the highest nutritional yield (in either protein or iron, respectively) replaced rainfed rice, provided that the nutritional yield of the replacing crop was higher than that of rice. Additional supplementary constraints were also applied to all of the scenarios described above (table S4). These constraints were that a rice replacement could only occur if the replacing crop also had a nutritional yield in terms of calories (kilocalories per hectare) that was higher than that of rice and/or that only finger millet, pearl millet, or sorghum could be considered as replacing crops. In all replacement scenarios, we assume that the water resources available to rice are then made available to the replacing crop.

### Combining water use and nutrition

The conventional measure of WFP uses the units of cubic meters of consumptive water demand per ton (for example, $m^3$ $H_2O$ $ton^{-1}$) (*58*). To examine whether the relative ranking of crops changed in terms of water productivity, we calculated the nutritional WFP values of crop $i$ in district $j$ as

$$\mathrm{WFP}_{i,j,n} = \frac{10\mathrm{CWR}_{i,j}a_{i,j}}{p_{i,j}c_{i,n}} \tag{6}$$

where $p_{i,j}$ is production (metric tons) and $c_{i,n}$ is the crop content of nutrient $n$ (nutrient per ton of crop). We used the nutrient content values reported for the most consumed form of each crop (table S8). Under all scenarios, the production of nutrient $n$ in district $j$ was calculated as

$$p_{n,j} = \sum(c_{i,n}y_{i,j}a_{i,j}) \tag{7}$$

where $y_{i,j}$ is the yield of crop $i$ and $a_{i,j}$ is the intended (irrigated or rainfed) area for crop $i$. Total minimum nutrient production required to meet DRI for the country (if there were no limitations on access and distribution and no losses or waste) was calculated by Rao *et al.* (*25*) based on Indian DRIs (*23*), which depend on age and gender, and year 2011 population statistics. Minimum required nutrient supply from cereals was then calculated as the product of total minimum required nutrient production for the entire Indian diet and the fraction of nutrients provided by cereals under current consumption patterns (table S4) (*25*). The minimum required nutrient supply used here assumes no limitations on access and distribution and no losses or waste; actual nutrient supply within the country would need to be above these values to overcome these barriers. DRI values were not provided for dietary fiber.

## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/7/eaao1108/DC1

Table S1. CWRs by district (mm $H_2O$ $year^{-1}$) for rainfed and irrigated crops.
Table S2. National production changes for kharif (monsoon) cereals under replacement scenarios.
Table S3. Cumulative water savings and changes in nutritional output from replacement scenarios.
Table S4. Outcomes and descriptions of rice replacement scenarios.
Table S5. Cereal consumption by crop and by district.
Table S6. State-level yields of kharif crops and outcomes of rice replacement scenarios.
Table S7. Crop-specific nutrient content reported in the National Institute of Nutrition's Indian Food Composition Tables.
Table S8. List of crop coefficient ($k_c$) values disaggregated by crop, climate zone, and month.
Table S9. State-level planting dates (month) for each cereal crop and growing season.
Table S10. Rooting depths for rainfed and irrigated crops as reported by Siebert and Döll (*37*).
Fig. S1. Geographic distribution of total CWR (mm $H_2O$ $year^{-1}$) of Indian cereals in irrigated lands.
Fig. S2. Geographic distribution of the fraction of total CWR of Indian cereals in irrigated lands met by blue water.
Fig. S3. Map of states based on 1966 boundaries.
Fig. S4. Time series of Indian cereal production and extent.
Fig. S5. Kharif production fractions by crop.
Fig. S6. Comparison of blue water use and nutrient yields of kharif (monsoon) cereals.
Fig. S7. District-level water savings of scenario 1 (rice replacement with the lowest total WFP cereal).
Fig. S8. Changes in nutrient production under scenario 1 (lowest total WFP).
Fig. S9. Current rice yield and yield differences of replacing crop on irrigated croplands.
Fig. S10. Ratio of most consumed alternative kharif cereal to rice.
Fig. S11. Iron as an example of change in per-capita nutrient production.
Fig. S12. Map of climate zones.

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