AGRICULTURE

Groundwater depletion will reduce cropping intensity in India

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Groundwater depletion is becoming a global threat to food security, yet the ultimate impacts of depletion on agricultural production and the efficacy of available adaptation strategies remain poorly quantified. We use high-resolution satellite and census data from India, the world's largest consumer of groundwater, to quantify the impacts of groundwater depletion on cropping intensity, a crucial driver of agricultural production. Our results suggest that, given current depletion trends, cropping intensity may decrease by 20% nationwide and by 68% in groundwater-depleted regions. Even if surface irrigation delivery is increased as a supply-side adaptation strategy, which is being widely promoted by the Indian government, cropping intensity will decrease, become more vulnerable to interannual rainfall variability, and become more spatially uneven. We find that groundwater and canal irrigation are not substitutable and that additional adaptation strategies will be necessary to maintain current levels of production in the face of groundwater depletion.

INTRODUCTION

Groundwater is a critical resource for food security, providing 40% of the world's irrigation (*1*). Millions of farmers depend on groundwater irrigation to help produce 40% of the world's agricultural production, including a large proportion of staple crops like rice and wheat (*2*). Yet, groundwater reserves are becoming rapidly depleted in many important agricultural regions across the globe (*3*). While the extent of current and projected groundwater depletion is well documented (*4*, *5*), the potential impact of this depletion on food production remains poorly quantified. Furthermore, it is unclear whether there are any adaptation strategies that may reduce the projected negative impacts of groundwater depletion on agricultural production. Yet, such information could help identify which adaptation strategies should be prioritized in which regions to ameliorate and avoid large production losses in the areas most at risk for groundwater depletion.

It is especially critical to quantify the impacts of groundwater depletion on crop production in India—the world's largest consumer of groundwater—where groundwater provides 60% of the nation's irrigation supply (*1*, *2*). Tube well construction has rapidly increased since the 1960s across India, allowing farmers to increase cropping intensity, or the number of seasons when crops are planted in a given year, by expanding production into the largely dry winter and summer seasons (*6*). This increase in cropping intensity is credited for much of the food production gains achieved over the past 50 years across India. However, because of high rates of extraction, aquifers are rapidly becoming depleted across much of India, with the northwest and south predicted to have critically low groundwater availability by 2025 (fig. S1) (*4*, *7*, *8*). This is of concern given that India produces 10% of global agricultural production and is the second largest producer of wheat and rice (*9*, *10*). Furthermore, a majority of India's rural population, approximately 8% of the world's population, depends on agriculture as a primary livelihood, and a reduction in agricultural production will negatively affect household welfare (*11*, *12*).

Very few studies have attempted to quantify the potential impacts of groundwater depletion on agricultural production in India. To date, efforts have largely relied on modeling approaches (*13*, *14*), which necessarily make assumptions about the relationship between groundwater use and crop productivity. With such an approach, it is difficult to account for real-world constraints that may reduce the efficiency of groundwater use, such as inefficient pumps and the inability of some farmers to irrigate at full capacity. Accounting for these limitations is particularly critical in regions like India, where water use efficiency is low and extremely heterogeneous across the country (*15*). Only one previous study (*16*) has incorporated empirical data on the relationship between irrigation use, crop production, and groundwater depletion. However, because of data limitations, this study relied on coarse district-level agricultural census statistics that do not distinguish between whether a crop is irrigated by groundwater or other sources, like canals. Thus, to date, it has not been possible to empirically estimate the association between groundwater use, crop production, and groundwater depletion, which is critical for accurately estimating the potential production losses that may occur when overexploited groundwater is lost.

We overcome previous challenges to empirically estimate the impacts of groundwater loss on agricultural production by using a novel satellite data product that we developed that measures winter cropped area, the key determinant of cropping intensity, at fine spatial resolution (1×1 km^2) across India (Fig. 1) (*17*). We link these data with high-resolution village-level census data on the amount of shallow well, deep well, and surface water irrigation in each village. We focus on winter cropped area because almost all farmers plant crops during the monsoon season (*18*, *19*), few farmers plant crops during the dry summer season (*19*), and winter agriculture is primarily dependent on groundwater for irrigation (*2*). We also assess the effectiveness of a potential supply-side government policy, namely,

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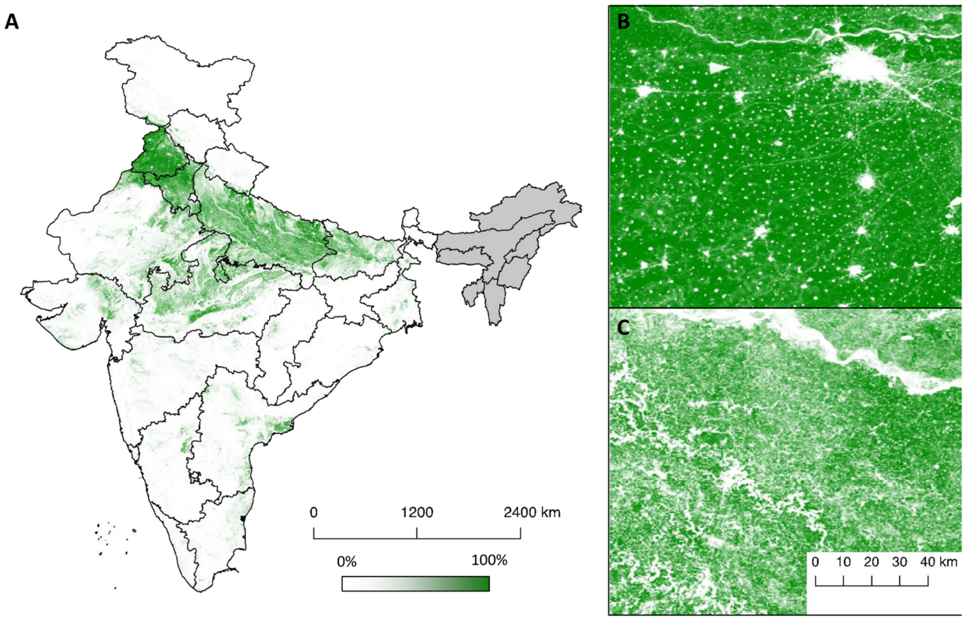

Fig. 1. Mean winter cropped area from 2000–2001 to 2015–2016 Cropped area is shown (A) across India, (B) in a highly cropped region in Punjab, and (C) in a medium-intensity cropped region in Bihar. Pixels that were never cropped are highlighted in white, pixels that were 100% cropped across all 16 years are highlighted in dark green, and pixels for which we do not have cropped area data are highlighted in gray.

expanding canal irrigation to regions that are facing severe groundwater depletion. We focus on this potential adaptation strategy because canal expansion is being widely promoted by the Indian government as a way to deliver irrigation water to regions with dwindling groundwater resources (*20*–*23*). By using high-resolution data on irrigation and agricultural production, we are able to directly link measures of crop production with specific types of irrigation infrastructure, providing information about their relative efficacies. In addition, because the efficacy of groundwater and canal irrigation likely varies across the country depending on local investments in infrastructure and on a region's climate and geology, these high-resolution data allow us to quantify this heterogeneity.

Using these high-resolution data, we empirically estimate what losses to production may occur if farmers lose access to critically depleted groundwater in the future and how effective canal expansion may be as an adaptation strategy. Specifically, we ask the following: (i) What is the relative influence of groundwater versus canal irrigation on winter cropped area and its resilience to rainfall variability across India? (ii) Do these effects vary regionally? (iii) What are the effects of irrigation source on spatial patterns of winter cropped area, a measure of irrigation equity across villages? and (iv) What may be the impacts on winter cropped area if critically depleted regions lose access to groundwater and transition to using canal irrigation? The results of this study offer insights into the food and livelihood security of millions of people and into the impacts of groundwater depletion and potential adaptation strategies in other regions dependent on aquifers at risk of depletion.

RESULTS

Canals are associated with less winter cropped area and greater rainfall sensitivity

To identify whether canal irrigation can serve as an adequate substitute for groundwater irrigation, we examined the relative influence of India's three main irrigation types on winter cropped area: dug wells (dug or sunk wells that primarily draw water from shallow depths <30 m), tube wells (drilled bore holes that primarily draw water from deeper depths >30 m), and canals [man-made delivery channels of diverted surface water; (*15*)]. We consider shallow groundwater sources, drawn from dug wells, and deeper groundwater sources, drawn from tube wells, separately in our analyses. Losing access to tube wells due to groundwater depletion is of particular concern as this irrigation source typically has the largest storage capacities and provides an annual irrigation output that is much greater than shallower wells (*15*). To assess the relative association between dug well, tube well, and canal irrigation and winter cropped area, we ran linear regressions where we restricted our analyses to villages that only had one type of irrigation source, and we treated irrigation type as a categorical variable. Doing this allowed us to assess whether each irrigation type had a statistically different effect compared with tube wells, when tube wells were selected as the reference category (Fig. 2, A to D), and with dug wells, when dug wells were selected as the reference category (Fig. 2, E to H). This analysis allowed us to isolate the individual effect of each irrigation source on winter cropped area without the possibility of multiple irrigation sources confounding our results. We also included an interaction term between annual rainfall and irrigation source to examine the sensitivity of winter cropped area to interannual rainfall variability based on irrigation type.

Across India, we find that tube well irrigation use is associated with a higher likelihood that farmers plant crops in the winter growing season (Fig. 2A), a higher proportion of cropped area in villages growing a winter crop (Fig. 2B), a lower coefficient of variation in cropped area (Fig. 2C), and less sensitivity of cropped area to monsoon rainfall variability when compared with the use of canal and dug well irrigation sources (Fig. 2D and table S1). Specifically, our regression results show that farmers in canal-irrigated villages are 52% less likely to plant a winter crop than farmers in tube well–irrigated villages (Fig. 2A). Furthermore, farmers in canal-irrigated villages

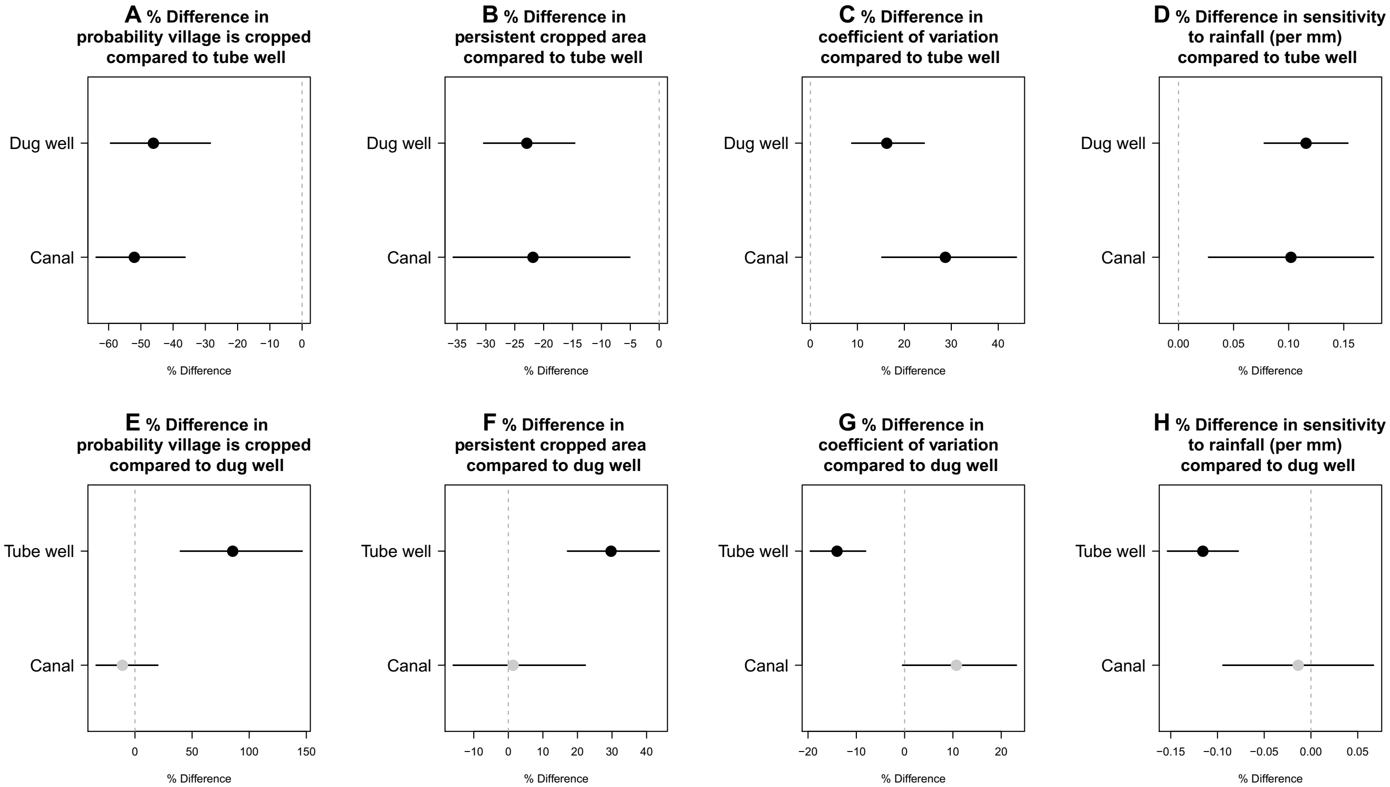

Fig. 2. Association between irrigation source and cropping intensity. Exponentiated regression coefficients and confidence intervals when estimating the percent difference compared with tube well irrigation in (**A**) the probability of ever having a winter crop, (**B**) persistent cropped area (mean from 2000–2001 to 2015–2016), (**C**) the coefficient of variation of cropped area, and (**D**) sensitivity of cropped area to interannual rainfall variability (per mm/day of rainfall) when using dug or canal well irrigation. (**E** to **H**) Exponentiated regression coefficients and confidence intervals when estimating the percent difference compared with dug well irrigation for these same metrics. Significant coefficients ($P < 0.05$) are highlighted in black, and nonsignificant coefficients are highlighted in light gray.

who do plant a winter crop have only 78% (or 22% less) of the winter cropped area found in similar tube well–irrigated villages (Fig. 2B). By comparison, we find no significant differences between the association of winter cropped area and dug well versus canal use (Fig. 2, E to H, and table S2). These results and all subsequent results are robust to the inclusion of a suite of biophysical and socioeconomic factors as controls to cross-sectional regressions (table S3), state as a fixed effect in all cross-sectional regressions, village as a fixed effect in panel regressions, and clustered SEs at the district scale in all regressions to account for spatial autocorrelation across villages. To test for robustness of these analyses, we ran additional tests in which district was included as a fixed effect and irrigation source was defined in multiple ways, such as including villages that use multiple sources of irrigation and defining irrigation as a continuous variable instead of a categorical variable (tables S1, S2, and S4). We find that the results from these robustness checks are qualitatively similar to the main results presented in this paper.

To examine potential heterogeneity in the relative efficacy of canals versus groundwater across India, we conducted the same analyses described above but for each state individually. We find that the associations between tube well, dug well, and canal irrigation and winter cropped area vary greatly across the country, with some regions showing little differences (e.g., western Indo-Gangetic plains), some regions showing greater cropped area associated with tube well irrigation (e.g., northwest India), and some regions showing greater cropped area associated with canal irrigation (e.g., South India; Fig. 3). Results for the tube well (Fig. 3, A to D, and table S5) and dug well (Fig. 3, E to H, and table S6) analyses were largely similar in sign across the country, although coefficients from the dug well analyses were often smaller in magnitude and insignificant, further suggesting that canals perform similarly to dug wells across much of the country.

Canals are associated with increased inequity in winter cropped area

Groundwater may lead to a more equitable distribution of irrigation across villages than canals, as the creation of wells is more decentralized than large-scale canal projects (*24*). In addition, previous studies have suggested that farms located downstream of storage reservoirs within a canal network receive less water (*25*) due to reduced downstream water flow caused by unregulated water use upstream, seepage, and evapotranspiration (*26*). We therefore examined whether canal irrigation is associated with increased spatial heterogeneity in cropped area compared with tube well and dug well irrigation. If villages have equal access to irrigation, we expect that there will be little variation in cropped area across villages. However, if villages have unequal access to irrigation, there will likely be large differences in cropped area across villages resulting in larger spatial heterogeneity. We find that distance to canal is strongly associated with less cropped area and greater sensitivity to rainfall variability in canal-irrigated villages (table S7). This suggests that while canals may be a viable form of irrigation for those who live near canals, they may lead to more unequal access to irrigation across villages compared with wells, with negative impacts for those who live farther from canals. We also calculated the coefficient of variation in mean cropped area across space within districts for all villages that were irrigated by canals, tube wells, or dug wells. We find that increased area under canal irrigation is associated with a significant increase in the coefficient of variation of cropped area across villages (table S7), suggesting that canal irrigation may lead to increased spatial heterogeneity and a less equal distribution of cropped area within a given district compared with groundwater irrigation.

Canal irrigation cannot substitute for groundwater irrigation in critically depleted regions

Last, we estimated what changes to winter cropped area may occur if farmers lose access to tube and dug well irrigation in critically depleted regions. These critically depleted regions (fig. S1C) are defined as areas that currently have long-term declines in groundwater depth (fig. S1A) and are expected to face the highest levels of groundwater stress in 2025 (fig. S1B) according to the Central Ground Water Board, India's national government agency that monitors groundwater (*7*). Specifically, these regions (i) are facing long-term groundwater depletion trends, as defined using multidecade well depth data from 20,000 wells across the country (table S8), and (ii) will face low future water availability, as defined using hydrological model simulations parameterized using these well data (see Materials and Methods for more details) (*5*, *7*). The critically depleted regions (fig. S1C) largely align with those found in previous independent studies that empirically examine where water tables are falling across India (*5*) and are projected to face continued depletion in 2050 using econometric and hydrological model simulations (*16*).

We find that approximately 13% of the villages in which farmers plant a winter crop are located in these critically depleted regions, and these villages may lose 68% of their cropped area in the future if access to all groundwater irrigation is lost. If we consider what these losses mean for national production, we find that national winter cropped area may decrease by 20% if farmers lose access to all groundwater in these critically depleted regions. Our results suggest that these losses will largely occur in northwest and central India (Fig. 4A). This scenario serves as an upper bound for the potential impact of groundwater depletion on winter cropped area across India, because it assumes that farmers that draw water from deep alluvial aquifers will choose not to irrigate due to increased drilling and pumping costs, salinization has occurred in coastal aquifers due to salt water intrusion, and shallow hard rock aquifers are not adequately recharged because of low rainfall, leading to 100% loss of groundwater in these critically depleted regions.

We next assessed how much of this loss may be mitigated if farmers who currently use wells in critically depleted regions will switch to using canal irrigation. This scenario provides an upper bound for the potential replacement capacity of canals, given that it is the most optimistic scenario where there are no infrastructural or physical limitations to expanding canal irrigation to all fields currently irrigated by groundwater. We find that winter cropped area may decrease

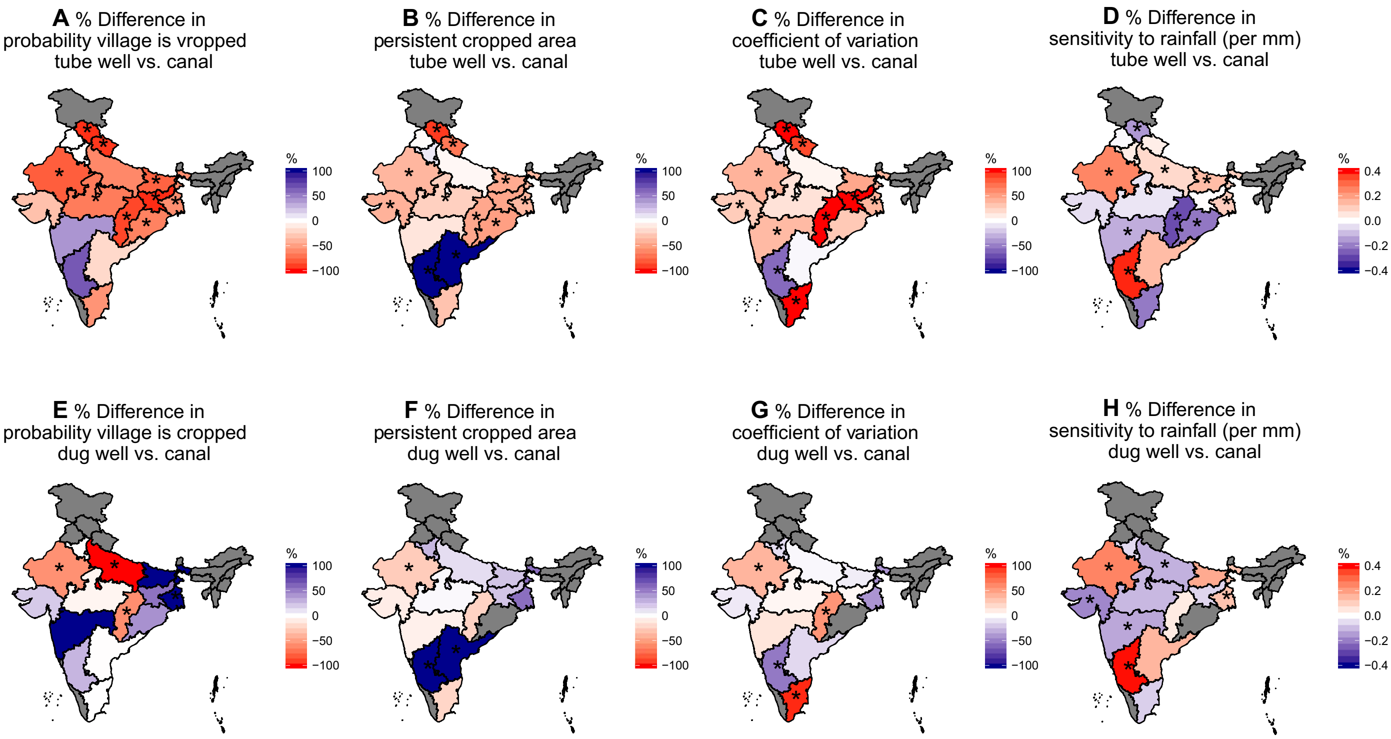

Fig. 3. State-by-state differences in the association between irrigation source and cropping intensity. Maps showing state-specific exponentiated regression coefficients for canal-irrigated villages compared with tube well–irrigated villages when estimating (**A**) whether a village was ever cropped, (**B**) the mean winter crop area for cropped villages, (**C**) the coefficient of variation of cropped villages, and (**D**) the sensitivity of winter crop area to interannual rainfall variability. (**E** to **H**) State-specific exponentiated regression coefficients for canal-irrigated villages compared with dug well–irrigated villages for these same metrics. Significant results for a given state are highlighted with an asterisk. States for which we did not have cropped area data or where regressions could not be run because of limited variation in irrigation source are highlighted in gray.

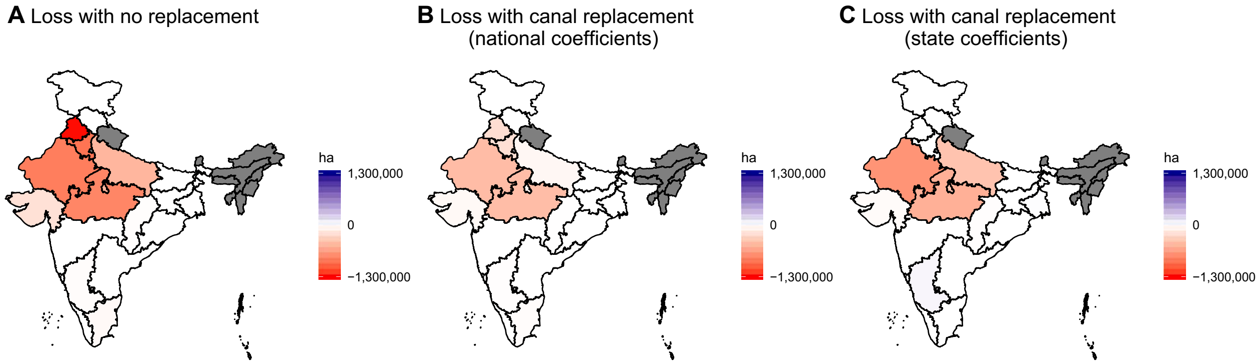

Fig. 4. State-by-state winter cropped area loss estimates due to groundwater depletion with and without replacement with canals. Maps showing state-specific estimates of winter cropped area loss (in red) and gain (in blue) (**A**) if all critically depleted groundwater is lost with no replacement, (**B**) if groundwater irrigation is replaced with canals (using national-level regression coefficients), and (**C**) if groundwater irrigation is replaced with canals (using state-level regression coefficients).

by 21.5% in critically depleted regions using coefficients for the difference in cropped area between well- and canal-irrigated villages in all-India analyses (Fig. 2, A, B, E, and F) and by 24% using coefficients from state-by-state analyses (Fig. 3, A, B, E, and F). If farmers will switch to using canal irrigation, we estimate that national winter cropped area may decrease by 6.33% using all-India coefficient values (Fig. 2, A and B) and by 7.05% using coefficients from state-by-state analyses (Fig. 3, A and B). These estimates were also calculated using 95% confidence intervals (values range from 3.3 to 8.0%) and similarly show that switching to canal irrigation will likely lead to reductions in winter cropped area nationwide. Specifically, losses will be largest in northwest and central India, and any potential gains from switching to canal irrigation in South India are not enough to offset these large losses (Fig. 4, B and C). These results largely align with those found in previous studies that have estimated the impacts of groundwater depletion on crop production, although we find larger losses in central India than do existing studies [e.g., (*13*, *16*)]. These results suggest that switching to canal irrigation can partially compensate for losing access to critically depleted groundwater but cannot match current levels of production. This is particularly true for villages that are primarily irrigated by tube wells (Figs. 2 and 3).

DISCUSSION

Greater irrigation access, driven by the expansion of tube wells, has been the primary driver of India's impressive food production gains over the past 50 years. This expansion has led to India becoming the largest consumer of groundwater worldwide and to severe groundwater depletion in many parts of the country. Despite the widespread knowledge that groundwater depletion is occurring and will likely have large negative ramifications for food security, the extent of crop production loss and whether there are any viable adaptation strategies remain unknown. Yet, such information is critical for identifying successful policy interventions that will help India maintain production levels in the face of groundwater depletion. Using a novel high-resolution dataset on cropping intensity, irrigation access, and groundwater depletion, we empirically estimate the potential impacts of groundwater depletion on agricultural production across India, and we find that these effects are large. Specifically, groundwater depletion may reduce cropping intensity by up to 20% across all of India and by up to 68% in the regions projected to have low future groundwater availability in 2025. These large projected losses are of concern given that India is one of the largest agricultural producers worldwide, and over 600 million farmers depend on Indian agriculture as a primary source of livelihood.

While canals are being promoted as an alternative irrigation source and as a supply-side adaptation strategy to falling groundwater tables, our results show that switching to canal irrigation has limited adaptation potential at the national scale. We find that even if all regions that are currently using depleted groundwater for irrigation will switch to using canal irrigation, cropping intensity may decline by 7% nationally and by 24% in the regions projected to have low groundwater availability. In addition to losses in overall production, we find that switching to canal irrigation will likely increase the sensitivity of agricultural production to rainfall variability and increase disparity in irrigation access across villages. Such reductions in production are of concern given that reduced irrigation access has been shown to be associated with reduced household income (*27*, *28*), increased rural poverty (*20*, *29*), and reduced household dietary diversity (*30*). These results highlight the importance of groundwater irrigation for Indian agriculture and rural livelihoods and that simply providing canal irrigation as a substitute irrigation source will likely not be enough to maintain current production levels in the face of groundwater depletion.

We find that canal irrigation may serve as a viable substitute for groundwater irrigation in certain parts of the country despite having limited capacity as an adaptation strategy at the national scale. Specifically, canal irrigation is associated with equal crop production as groundwater irrigation in the western Indo-Gangetic plains and with increased crop production in South India. This variation in canal efficacy is likely due to differences in aquifer geology, irrigation policies and subsidies, and historical investment in irrigation technologies. For example, in the western Indo-Gangetic plains, there has been a long history of investment in canals, resulting in higher irrigation output compared with canals in other parts of India (*31*). In South India, wells are not as high yielding as in other parts of the country because they are drilled into shallow hard rock aquifers that deplete and replete annually, making wells perform similarly to canals (*32*). While canals have the potential to adequately serve as a substitute irrigation source in South India, this region will likely not be able to compensate for potential losses to production projected in Central and North India (Fig. 4, B and C). This is because South India produces a small fraction of the nation's winter crop (Fig. 1), and the entirety of India's wheat is planted in Central and North

India during the winter growing season (*33*, *34*), suggesting that there may be large reductions in national wheat production if farmers switch away from groundwater to canal irrigation in the future. This is of concern given that India is the second largest producer of wheat globally (*10*), and wheat provides approximately 20% of household calories across the country (*35*).

This study highlights the critical importance of groundwater for agriculture in India and that additional adaptation and policy strategies are needed along with canal expansion to cope with impending groundwater loss. For example, policies that reduce the demand for groundwater, such as switching to less water-intensive cereals, could be one way to reduce pressures on existing groundwater reserves (*36*). In addition, policies that promote increased field-level water use efficiency, such as the adoption of water-saving technologies like sprinkler and drip irrigation, may help use what limited groundwater resources are left more effectively (*37*). Last, policies could target ways to increase the efficiency of canals across India. Previous studies have suggested that current canal irrigation efficiency is suboptimal (*25*) and could likely be increased at relatively low cost. Our results highlight that the trade-offs between using groundwater versus canal irrigation must be considered when designing local to national policies to address the looming threat of groundwater depletion on agricultural production. Transitioning to using canal irrigation in most regions of India will not be sufficient, and simultaneous water conservation investments will have to be made to encourage farmers to switch to less water-intensive crops and improve field-level water use efficiency to maintain current production levels in the face of falling groundwater tables.

MATERIALS AND METHODS

Experimental design

We compiled several different datasets on crop production (from remote sensing estimates of winter cropped area), irrigation (from the Indian government's minor irrigation census), socioeconomic and biophysical controls (from the Indian government's census statistics), and future groundwater availability (from the Central Ground Water Board of the Indian government) for each village in India. Each dataset is described in the "Datasets" section below. We then ran linear regressions to estimate the relative difference in cropped area between tube well–, dug well–, and canal-irrigated villages. We also examined the impact of canal irrigation on equity of cropped area across villages. These methods are described in the "Statistical analysis" section. Last, we simulated what future losses to crop production may be if farmers in areas with critically depleted groundwater will lose access to groundwater, and how much of this loss could be ameliorated if farmers will transition to using canal irrigation. These methods are described in the "Scenario analysis" section.

Datasets

Data were collated at the village scale by compiling several different datasets. Village winter cropped area, which was used as the dependent variable in all analyses, was calculated by extracting the mean annual winter cropped area produced by Jain *et al.* (*17*) to the village scale using village-level boundaries from ML Info Map. Irrigation data were compiled from the third Minor Irrigation Census (2001) and the Village Amenities Survey (2012) produced by the Indian Government Ministries. Because of changes in village, district, and state names across these datasets, we were able to match 60% of all villages in India across these three datasets, reducing our sample size from 568,990 villages to 341,834 villages. We used information from both irrigation datasets to define irrigation type for each village, which also helped ensure that the type of irrigation used in each village was constant from 2001 to 2012 (the majority of our study period). Irrigation was defined differently in each dataset, with the 2001 dataset including detailed information on all minor irrigation structures but missing information on medium and major canal projects, and the 2012 dataset including information on all irrigation used in a village, without differentiating between groundwater sources (e.g., tube well versus dug well). Therefore, we defined tube well villages as those that (i) had only tube well irrigation in 2001 and (ii) had only well irrigation in 2012. Dug well villages were defined as those that (i) had only dug well irrigation in 2001 and (ii) had only well irrigation in 2012. Canal villages were defined as those that (i) only had canal irrigation in 2012 and (ii) had no well irrigation in 2001. Additional socioeconomic, demographic, and biophysical data were used from different data sources (table S3). Distance to canals was calculated using the nearest distance algorithm in QGIS and a shapefile on global canals produced by the Digital Chart of the World (2009).

Statistical analysis

We log transformed cropped area in all regressions to achieve normality; original values ranged from 0 to 100, so 1 was added before conducting log transformations. To examine the relative influence of groundwater versus canal irrigation on cropping intensity, we ran eight sets of regressions (tables S1 and S2). The dependent variables in each regression were (i) a binary variable if the village was ever cropped between 2000 and 2016, (ii) mean cropped area from 2000 to 2016 that represents persistent cropped area across villages, (iii) the coefficient of variation in cropped area from 2000 to 2016 for each village, and (iv) annual cropped area estimates in all regressions that examined the sensitivity of cropped area to rainfall variability (the interaction between irrigation type and annual monsoon rainfall). Four sets of regressions used tube wells as the reference irrigation source (table S1), and four sets of regressions used dug wells as the reference irrigation source (table S2) to identify the differential impact of canals on each type of well. We also ran these same regressions for each state by subsetting the data to include only villages within a given state (tables S5 and S6). To ensure that the associations we observed between irrigation and cropped area could be attributed to a specific irrigation source, we restricted all analyses to villages that only have one type of irrigation during our study period. All analyses were done using R Project Software unless otherwise noted.

To analyze the impact of irrigation type on the spatial heterogeneity of cropped area, we ran three different regressions (table S7). First, for only canal-irrigated villages, we ran regressions that examined the relationship between distance to the closest canal and mean cropped area from 2000 to 2016. Second, we examined the association between distance to canal and sensitivity to rainfall variability by using annual cropped area estimates as our dependent variable and interacting distance to canal with annual monsoon rainfall. Last, we examined the association between the coefficient of variation in mean cropped area across villages for both canal- and well-irrigated villages and the percentage of the district that is under canal irrigation. This analysis identifies whether increased area under canal irrigation results in increased spatial heterogeneity in cropped area, suggesting increased inequity in irrigation access across villages.

To reduce issues of endogeneity in all analyses, we included a large number of biophysical (e.g., soil type) and socioeconomic (e.g., household assets) confounding factors as controls in all cross-sectional analyses (table S3). Furthermore, we included state as a fixed effect in all cross-sectional regressions and village as a fixed effect in panel regressions. To reduce the effect of spatial autocorrelation, we also clustered SEs at the district scale in all regressions. Last, we ran two robustness checks for all India-wide regressions, either including a district fixed effect or expanding our village sample to include villages that use irrigation from multiple sources (tables S1, S2, S5, and S6). In addition, we ran a robustness check where we defined our independent irrigation variable as the area under each irrigation type (in hectare; table S4). The sign, magnitude, and significance of results remain similar with these robustness checks. *P* value and sample size are reported in the associated tables for each regression in the Supplementary Materials. Formulas for the main regressions presented in this paper and the structure of our datasets are outlined in table S9.

Scenario analysis

Last, to estimate the impacts of losing access to groundwater irrigation and transitioning to canal irrigation on national winter crop production, we identified whether a village was located in a "critically depleted region," which was defined using two criteria, both of which a village had to meet. The first was that the village was located in a block (administrative below district) that has been classified by the Indian Government's Central Groundwater Board (CGWB) as one where long-term trends from in situ well data suggest groundwater depletion (semicritical, critical, and overexploited blocks; fig. S1A). The CGWB identified these long-term trends using data from 20,000 empirically measured test wells across India from 1998 to the present. Groundwater depletion was defined using at least 10 years' worth of well data, in which at least 10 to 20 cm of water level decline has occurred in the premonsoon and/or postmonsoon period (*5*). In addition, we identified whether the village was located within a district that is projected by the CGWB to have low to low-medium availability of groundwater in 2025 (fig. S1B). These regions were defined as having low future availability based on projected available volume, given net annual groundwater availability, projected demand for domestic and industrial uses in 2025, and gross irrigation draft of current groundwater (*5*). We independently verified that "critically depleted" blocks had significantly deeper well depths (14.15 m versus 8.84 m) and greater depletion rates [loss (0.99 m/year) versus gain (0.58 m/year)] than those categorized as "safe" using data from the 20,000 test wells collected by the CGWB (table S8). We compared these critically depleted regions with regions defined as groundwater depletion hot spots in previous studies [e.g., (*3*–*5*)] and found that the regions largely align, although other studies have estimated more depletion in northeastern India (*5*) and Gujarat (*3*) than does our study.

We focused on all areas under groundwater irrigation, either from tube wells or dug wells, for our scenarios. Percentage of cropped area under tube well and dug well irrigation was extracted from the minor irrigation census dataset. Because we could only match approximately 60% of villages using minor irrigation data at the village scale, we used information on percentage of area under dug and tube wells at the district scale, which allowed us to match and use the full village dataset (n = 568,990) for our scenario analysis. For the scenarios in which access to groundwater irrigation is lost with no replacement, we subtracted the cropped area under tube and dug well irrigation in critically depleted regions from the original total national cropped area. For the scenarios in which these areas are replaced with canal irrigation, we used the coefficients for canal irrigation derived from our national-level analyses (tables S1 and S2) and state-specific analyses (tables S5 and S6) to assess the relative effect of canals compared with tube wells and dug wells on cropped area. We applied coefficients for both whether a farmer ever plants a winter crop or not (Figs. 2, A and E, and 3, A and E) and the change in cropped area when a winter crop is planted (Figs. 2, B and F, and 3, B and F). If state-level results did not exist because of limited irrigation data in that state, we used the all-India value for that state. We then subtracted the total cropped area produced under these scenarios from the original total national cropped area. To derive confidence intervals around these cropped area loss estimates, we also applied the lower and upper 95% confidence intervals for both the beta coefficient of canal irrigation for whether a village was cropped or not and the beta coefficient of canal irrigation for the percentage of cropped area in a given village.

Strengths and limitations

By using real-world production data, we were able to account for the complex institutional, economic, and social factors that determine realistic productivity estimates (*38*). This approach builds on previous work that has estimated the impacts of future climate change on irrigation access and crop production using model simulations (*13*), which often model crop production using assumptions of farmer behavior and decision-making. Our use of high–spatial resolution estimates of agricultural production instead of census statistics available at the district level enabled our study to overcome some limitations of previous studies. Village-level data allowed us to directly link a single irrigation source with its associated agricultural production, which is not possible to do using district-level data because both groundwater and canal irrigation are used within a single district. These high-resolution data also allowed us to examine the relative influence of groundwater and canal irrigation on the spatial heterogeneity of crop production across villages, which cannot be modeled using district-level data. Such analyses are critical for understanding the potential impacts of groundwater depletion on equity. Last, high–spatial resolution data allowed us to examine variation in the relative efficacy of groundwater versus canal irrigation across different states in India, which is important as our results showed that there is heterogeneity in efficacy across the country.

Our study was constrained to rely on cross-sectional irrigation data to estimate the association between irrigation source and winter cropped area because annual panel data on irrigation amount and source do not exist at the village-scale across India. However, we reduced the effect of endogeneity in our analyses by accounting for a suite of biophysical and socioeconomic variables (table S3) and included state fixed effects (and district fixed effects as a robustness check) to further reduce the effect of omitted variable bias. Our scenario analysis makes several assumptions. First, we assume 100% loss of access to critically depleted groundwater; however, it is likely that some farmers will maintain some access as water tables decline, either by paying higher costs or using annually refilled shallow aquifers. Work by Dar *et al.*, however, supports the assumption that farmers will lose access to irrigation as groundwater tables fall as they found that groundwater depletion is associated with reductions in winter cropped area across India. Second, we assume that canal irrigation will be able to reach all farmers that currently have access to well irrigation, yet there are likely physical and infrastructural constraints to expanding canal irrigation at such a scale. Third, we did not incorporate potential recharge to groundwater that may occur if canals are expanded, although previous work has shown that canal expansion will do little to reduce stress on overexploited aquifers (*16*). Fourth, our winter cropped area data do not distinguish between crop types, and it is possible that farmers are adapting to groundwater depletion by switching to less water-intensive crops; if this occurs, we likely would see smaller shifts in cropped area as groundwater tables fall because farmers are instead adjusting their crop portfolios. Last, we did not consider how increases in groundwater withdrawal in some parts of the country may be able to offset the effects of groundwater depletion in other parts of the country. For example, studies have suggested that eastern India (i.e., Bihar, Jharkhand, Odisha, and West Bengal) may be able to become the future bread basket of India as groundwater in this region has not been overexploited, and tube well infrastructure can be further developed. We find, however, that during the time period of our study, while area under groundwater irrigation increased in eastern India, we did not see an associated increase in winter cropped area (fig. S2). This suggests that, to date, increased groundwater irrigation in eastern India has not compensated for groundwater losses elsewhere, although it is possible that it may do so in the future, especially in states that are heavily investing in groundwater infrastructure such as Bihar. Our scenario analysis should be interpreted as an estimate of the maximum impact of future groundwater depletion and the maximum effectiveness of a canal expansion policy.

SUPPLEMENTARY MARTERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/9/eabd2849/DC1

View/request a protocol for this paper from *Bio-protocol*.

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