The role of farm subsidies in changing India's water footprint

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Dwindling groundwater supplies threaten food security and livelihoods. Output subsidies for farmers are a ubiquitous agricultural policy tool, yet their contribution to growing groundwater stress remains poorly quantified. We show how output subsidies guaranteeing the purchase of crops at higher than market prices may have contributed substantially to declining water tables in India. Our analysis suggests that these policies may have led to a 30% overproduction of water intensive crops. In the northwestern state of Punjab, rice procurement can potentially account for at least 50% of the groundwater table decline over 34 years. In the central state of Madhya Pradesh, wheat procurement adopted in the late 2000s appears to have driven a 5.3 percentage point increase in dry wells and a consequent 3.4 percentage point increase in deep tubewells. These results suggest that well-intentioned but poorly designed subsidies can impose harmful externalities on the environment and undermine long-term sustainable development.

India has witnessed a 500% increase in groundwater consumption over the past half-century[1–5], making it one of the greatest groundwater guzzlers in the world. Unsurprisingly groundwater reserves are depleting at an alarming rate[2,6]. Since the 1980s, groundwater levels have plunged by more than 8 meters on average and to 30 meters below ground level in some regions[7]. This trend is starkly visible in the alluvial aquifers of northwest India[2,7,8]. In central and south India, where wells deplete and replete annually due to the nature of the hardrock aquifer systems, these trends are less apparent. Here, other metrics of over-extraction, such as increases in the number of dry or defunct wells, reinforce the alarm[9] (Fig. S1).

Output subsidies are provided to farmers in India via guaranteed government procurement of water-intensive crops like rice and wheat at pre-determined prices. This policy was introduced during the Green Revolution of the 1960s in the Punjab region and has subsequently expanded to other states. The goal in the 1960s was to incentivize the adoption of high-yielding variety seeds to increase productivity and ensure food security for the nation. A second goal was to provide farmers with risk-free remunerative incomes[10] (Supplementary Information).

Researchers and experts have argued that while the policy was justifiable during the 1960s as India faced acute food scarcity, it is no longer optimal[11,12]. Now it may be causing unintended harm to food security, farmer incomes, and sustainability by accelerating groundwater depletion[13,14]. The underlying mechanism has two parts. First, the output subsidy is implemented mainly for rice and wheat and not other crops. Thus, rice and wheat cultivation has risen unchecked since the 1960s, engulfing other crops. Today, even as production of these crops exceeds national consumption needs and emergency buffer requirements by at least 30%, a guaranteed subsidy likely encourages continued cultivation of rice and wheat and keeps farmers from switching to other crops.

Second, since rice and wheat are water-intensive crops, their increased cultivation requires irrigation. Over time the increased irrigation needs have been met by personal irrigation systems like wells rather than surface water systems like dams or canals[3,4]. Together these trends have contributed to rapid declines in groundwater levels. Rice and wheat provide over 50% of the calorific intake of India's 1.4 billion people[15] and groundwater scarcity decreases crop yields[16,17]. Therefore, groundwater depletion compromises food security and farmer livelihoods[18] —the very objectives of the subsidy policy. Moreover, estimates suggest that in the long-run a complete loss in access to groundwater can reduce annual crop production by 28%, dry season crop production by 51%, and cropping intensity by 68%[19]. Furthermore,

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as groundwater also acts as a buffer against climatic variability, its depletion undermines adaptability to climate change[14,20].

Even as groundwater depletes, India's political economy contributes to the persistence of this policy[21]. Without a cap or a sunset clause, a vicious cycle has ensued. The deeper the groundwater table, the costlier the cultivation due to increasing costs for well deepening and pumps. As noted above, assured government procurement has locked in most of India's 260 million farmers into growing rice and wheat. Since the farmers are now wholly dependent on this policy for their incomes, the government is forced to increase the subsidy every year to cover increasing costs. This has resulted in India currently spending about USD 4 billion annually to fund the output subsidy program, albeit with substantial cross-state variation[22].

While the literature has focused on the role of input subsidies like free power[23,24], studies on the role of output subsidies in driving local water use is limited. This is both because the driving mechanisms are subtle, and there has been a lack of data to show them. Output subsidies affect groundwater indirectly by shaping crop choice decisions, unlike power subsidies that directly increase groundwater extraction using pumps. We contribute to this by collating data from several sources since 1981 and quantify the role of the output subsidy policy in eroding India's groundwater supplies.

Our analysis has three parts. First, we show that increased cultivation of a water-intensive crop like rice is closely tied to increases in groundwater stress across India. In particular, we show that across Indian districts, a 1 standard deviation increase in the rate of growth in the area under rice cultivation between 1996–2015 is associated with a 5.44 percentage point (pp) increase in defunct wells. Second, we argue that an excess of rice and wheat production by almost 30% is sustained because of the government's guaranteed purchase of these crops at higher than market prices. Third, we focus on case studies from two states with distinct aquifer systems to illustrate the main mechanism by which the output subsidy policy impacts groundwater. The hydrogeology and aquifer-specific properties can impact the extent to which pumping affects the water table locally[9,25]. For the state of Punjab, we show that the output subsidy policy has contributed to at least 50% of the local decline in the groundwater table. Since this region overlays deep alluvial aquifers, these effects manifest gradually. Results show that the effects of policy-induced groundwater extraction are fully reflected in declining water levels after 6-7 years. For the central Indian state of Madhya Pradesh, we use different metrics of groundwater stress since it predominantly overlays hard rock aquifers

with low storage capacity[9,25]. Here, results show that since the inception of the output subsidy policy in 2008, incidence of dry wells has increased by 5.3 pp and demand for deep tube wells by 3.4%. In general, showing that this is a pan-India issue affecting regions with very different hydrogeological conditions is important because agriculture policy related groundwater issues tend to be associated with northwestern India.

Thus, in this work, we show that the output subsidy policy is a significant driver of groundwater stress not only in the deep alluvial aquifers of northwestern India but also in the hard rock aquifers of central India. Additionally, we show that not paying attention to the nature of aquifers can lead to an underestimation of the effects of output subsidies on groundwater stress. This entails considering the gradual nature of adjusting groundwater tables in the alluvial aquifers of Punjab and using alternate groundwater stress metrics like dry wells and demand for deep tubewells in the hard rock aquifers of Madhya Pradesh. The results in this paper suggest that while the most common policy objectives of agricultural subsidies are to provide price stability and food security, and to support farmers' incomes and livelihoods, they can often lead to unintended consequences that are counterproductive to policy goals. By distorting crop and irrigation choices, such support can ultimately lead to harmful spillovers on local water resources and undermine sustainable development objectives in the long term.

Results
Cultivation of water-intensive crops, the role of output subsidies and groundwater stress in India
A significant factor contributing to groundwater stress in India is the over-production of water intensive crops like rice and wheat. For example, Fig. 1a shows that across Indian districts, a 1 standard deviation increase in the rate of growth in area under rice cultivation between 1996–2015 is associated with a 6.37 pp increase in active wells becoming defunct. This is not understandable given that rice is one of the most water intensive crops cultivated using flood irrigation technique[26,27].

The relationship in Fig. 1a could be confounded by other factors that are different across districts (Fig. S2). To address this, we estimate multivariate statistical models at the district level. Specifically, we regress the increase in defunct wells on the annual rate of growth in the area under rice cultivation, and control for the growth in area under other crops, initial area under rice cultivation, initial gross cropped
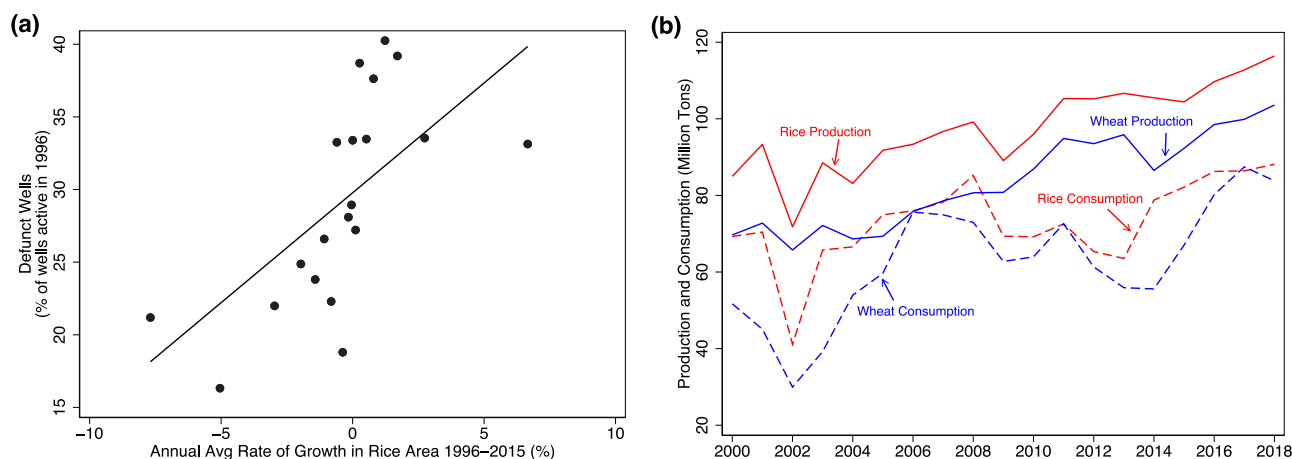
Fig. 1 | Over-production of water-intensive rice and wheat despite increased groundwater stress. a Groundwater stress and growth in rice area: Plots the output from a binned regression of defunct wells on annual average rate of growth of rice area. Each observation is a district. The average annual rate of growth in area under rice cultivation is divided into twenty equal bins. The scatter plots are the means of defunct wells and growth of rice area in each bin. The line is the OLS

relationship between defunct wells and the growth of rice area. **b** Excess Production of Rice and Wheat: Domestic consumption is estimated as total production−net exports−government stock. Sources: Agriculture Statistics at a Glance 2020; Directorate General of Commercial Intelligence and Statistics, Ministry of Commerce; and Department of Food and Public Distribution, Govt. of India.

Table 1 | Effects of rice cultivation on groundwater stress: All India

| | Defunct wells (as a % of active wells in 1996) | | | | | |
| | 1996–2015 | | | 1966–2015 | | |
	(1)	(2)	(3)	(4)	(5)	(6)
Avg. annual rice area growth	1.51***	1.52***	1.29***	3.42***	3.62***	3.00***
	(0.47)	(0.47)	(0.40)	(0.53)	(0.53)	(0.53)
	[0.001]	[0.001]	[0.001]	[3.2e-10]	[4.8e-11]	[3.5e-8]
Growth in area under other crops		✓	✓		✓	✓
Other Controls			✓			✓
N	279	279	278	294	294	292
Adj. R^2	0.03	0.04	0.27	0.13	0.14	0.31
Rice Area Growth (Std. Deviation)	4.22% per year			2.58% per year		

Notes: Each observation is a district. Robust standard errors clustered at the district level reported in parentheses and associated p-values reported in square brackets. Two-sided t-test used.
*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. The dependent variable in all columns is the percentage of wells that were active in 1996 but were defunct in 2015. Average Annual Rate of Growth of Rice Area or in area under other crops is calculated over 1996–2015 in cols 1–3 and over 1966–2015 in cols 4–6. Growth is measured in percent. Other controls include avg. annual precipitation, initial gross cropped area (GCA), initial rice area, land area of the district, and population.

area, total land area, average annual precipitation and population (Methods). Table 1, cols 1–3 show that an increase in rice area growth by 1 standard deviation during 1996–2015 is associated with an increase in defunct wells by at least 5.44 pp even after accounting for differences in other confounding factors. Since major increases in rice cultivation occurred immediately following the green revolution, when we consider the growth in rice cultivation from 1966 the estimated effects sizes double (Table 1, cols 4–6).

In many regions, farmers often rely on groundwater from deeper tubewells. Therefore, using similar statistical models we also show that a 1 standard deviation increase in the rate of growth of rice area is also associated with a 50% increase in the construction of tubewells between 1996 and 2015 (Supplementary Information, Table S1).

The increased groundwater stress from cultivation of rice may only be a symptom of the problem. The underlying mechanism is the implementation of the output subsidy policy which is inducing over-production. In principle, the central government commits to procure from farmers twenty-three crops at a pre-determined floor price (called the Minimum Support Price or MSP). However, in practice, the policy is implemented by government agencies primarily for rice and wheat—the main cereal crops (Supplementary Information). Thus, farmers are incentivized to increase the cultivation of rice and wheat over other crops in regions where this policy is implemented more intensively (Fig. S3). A notable exception is the eastern state of Odisha where substantial increases in procurement haven't necessarily increased groundwater usage. This is because most farmers in Odisha haven't directly benefitted from the procurement policy with only a few large farmers and traders in Odisha receiving incentives to increase irrigation[28].

Excess production of rice and wheat should ideally put downward pressure on rice and wheat market prices. This, in turn, should disincentivize their production and automatically contain the exploitation of groundwater. However, a guaranteed floor price to farmers cultivating rice and wheat for half a century has thwarted the discipline of market forces and resulted in the depletion of scarce groundwater reserves[29]. In 2020 alone, the national production of rice and wheat exceeded consumption by 30% and government reserves were nearly 2.5 times the required norms (Fig. 1b and S4a)—an excess of 36 million tons or about 20% of India's annual consumption. A large part gets wasted[30,31] turning the associated cost on groundwater into a potential deadweight loss.

Case studies
While the all-India analysis is telling, the main challenge in rigorously quantifying the role of MSP and public procurement in inducing the

production of rice and wheat and the subsequent effect on ground-water is the lack of spatially disaggregated and consistent data for key variables of interest—quantity of rice or wheat procured by government, cropped area, and groundwater—from a period when the policy-induced thrust toward the cultivation of rice and wheat occurred. To circumvent this issue, we focus on two states for which we were able to collect this data in different but relevant time periods, i.e., close to when the policy was instituted in the respective states—Punjab (1981–2003) and Madhya Pradesh (2002–2016) (Methods).

Case study I: Punjab
Although Punjab is one of the most agriculturally productive and irrigated regions of the country, it has also witnessed one of the largest increases in groundwater stress in the world[32]. The average ground-water depth increased from 4.82 mbgl in 1973 to 14.55 mbgl in 2016. By 1999, 78.6% of all dug wells that were active in 1973 had become defunct (Fig. 2a). Additionally, over 75% of the area is considered overexploited according to the Central Ground Water Board[25]. A key factor contributing to this depletion lies in the adoption of high-yielding variety (HYV) wheat and rice during the Green Revolution in the 1960s. These varieties replaced local wheat varieties, cotton, maize, and oilseeds (Fig. 2c and Supplementary Information, Table S3) and required more intensive irrigation. The increased irrigation came from groundwater (dug wells and tubewells) causing its depletion (Fig. 2b). Underlying this process was the policy of assured government procurement at MSP of rice and wheat (Fig. 2d), which incentivized cultivation of these water-intensive crops over others even as India amassed a surplus of rice and wheat.

The earliest year for which district-level procurement data are available is 1981. By this time, the wheat area had become stable with little change over time. On the other hand, rice area exhibits an increasing trend (Fig. 2c) and remains the focus of the analysis. Using regression models with a rich set of controls and fixed effects (Methods) we first document an output response. Farmers responded to a doubling of rice procurement by increasing area under rice cultivation by at least 25% in the following year (Supplementary Information, Table S4).

Second, to show how increased rice cultivation or procurement in turn impacts groundwater levels, we regress changes in groundwater levels on the log rice area or log rice procured (Methods). Since Punjab overlies thick and deep alluvial aquifers, adjustments in groundwater levels are gradual and can take time to manifest[33]. To capture these dynamics, we compute changes in groundwater level over multiple horizons and estimate a separate model for each horizon. We present these results graphically in Fig. 3a.
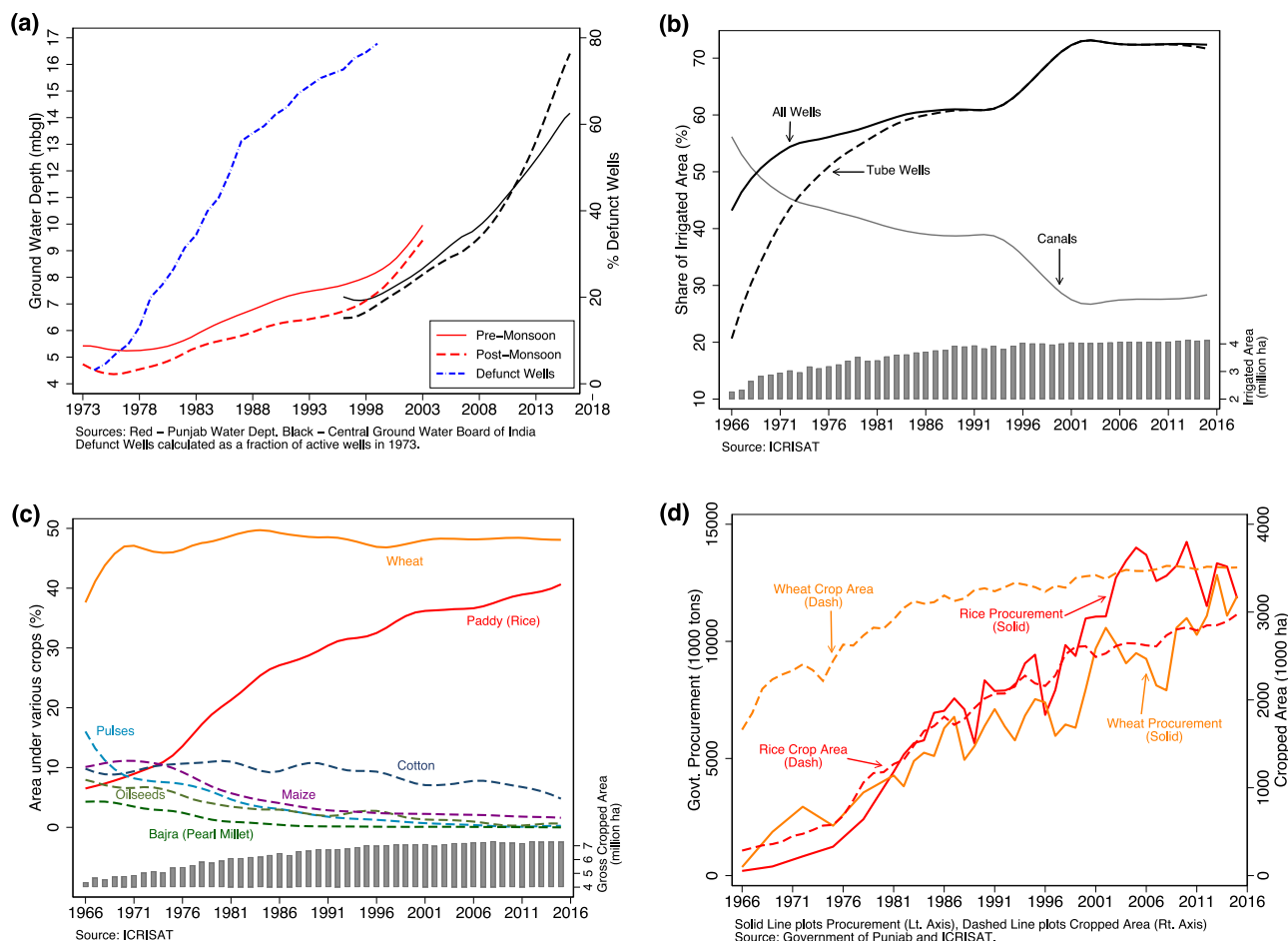
Fig. 2 | Trends in groundwater, irrigation, crops, and procurement in Punjab. **a** Trends in groundwater depth is plotted on the left y-axis and the fraction of defunct wells on the right y-axis. Fraction of wells defunct in any year are calculated over the base of wells that were active in 1973. Trends are estimated using local linear regressions with bandwidth 2.5. **b** Trends in share of irrigated area under all wells, tube wells, and canals are estimated using local linear regressions with bandwidth 2.5 and plotted on the left y-axis. The bars at the bottom plot irrigated area over time and must be read off the right y-axis. **c** Trends in cultivated area under various crops estimated using local linear regressions with bandwidth 2.5. The bars at the bottom plot gross cropped area over time and must be read off the right y-axis. **d** Solid lines plot trends in government procurement of rice or wheat (left y-axis) and dashed lines plot cropped area (right y-axis).

To understand Fig. 3, first pick a horizon. For example, the estimate at T = t + 4 is from a regression where the dependent variable is the proportional change in groundwater depth between an initial year t and t + 4, i.e. over four years (Δ = 4). The main co-variate of interest is either log rice area (Fig. 3a) or log rice procurement (Fig. 3b) in year t. Thus, the estimates show how the effects of the same "shock"−rice area or procurement in year t−manifests over different horizons. Estimates using pre-monsoon readings are in blue and those using post-monsoon readings in red. In all models, we control for various observable factors that could bias our estimates like population, net cropped area, precipitation, and temperature. To control for time-invariant, district-specific unobserved factors like geography, we use district fixed effects. We control for year fixed effects to isolate unobserved district-invariant, time-varying factors like global warming. We also include district-specific time trends that account for district-specific time-varying factors like changes in socio-economic indicators that could bias our results. Our results are also robust to explicitly including wheat area as a control, which is another water-intensive crop and is grown in the following cropping season. The rich set of controls helps us estimate the effect of rice cultivation on groundwater depth.

Figure 3a depicts how the effects on groundwater table depths manifest over time. A doubling of rice area (i.e. an increase by 100%) is associated with a fall in groundwater depth of 8 pp over a year and 28 pp over three years, as measured by post-monsoon readings. Similar patterns are observed for pre-monsoon readings. The effect keeps increasing until about six years and then stabilizes at 40 pp for pre-monsoon and 72 pp for post-monsoon readings.

In Fig. 3b, we regress proportional changes in groundwater depth directly on log rice procurement with the same set of controls. The effects show a similar evolutionary pattern. By the seventh year, which is when the effects stabilize, a doubling of rice procurement results in a 40 pp fall in groundwater levels. The gradual adjustment in groundwater table depths is an important empirical finding and worth emphasizing. A naive analysis that ignores the adjustment process and focuses solely on the contemporaneous relationship between changes in groundwater level declines and procurement might incorrectly conclude that the policy has had no impact on the environment.

Average groundwater depth in Punjab fell by about 100% between 1981 and 2015. During this period, rice procurement has increased at about 3% per year from 4.4 to 13 million tons. Our results suggest a fall of 1.2–2 pp per year in groundwater depth due to this mechanism or a total fall of 50–65% over 34 years. In other words, increased rice cultivation that was induced by government procurement of rice may account for at least 50% of the fall in groundwater levels in Punjab between 1981 and 2015.

If rice production or procurement increased in those districts where groundwater tables were already declining at a faster rate, then
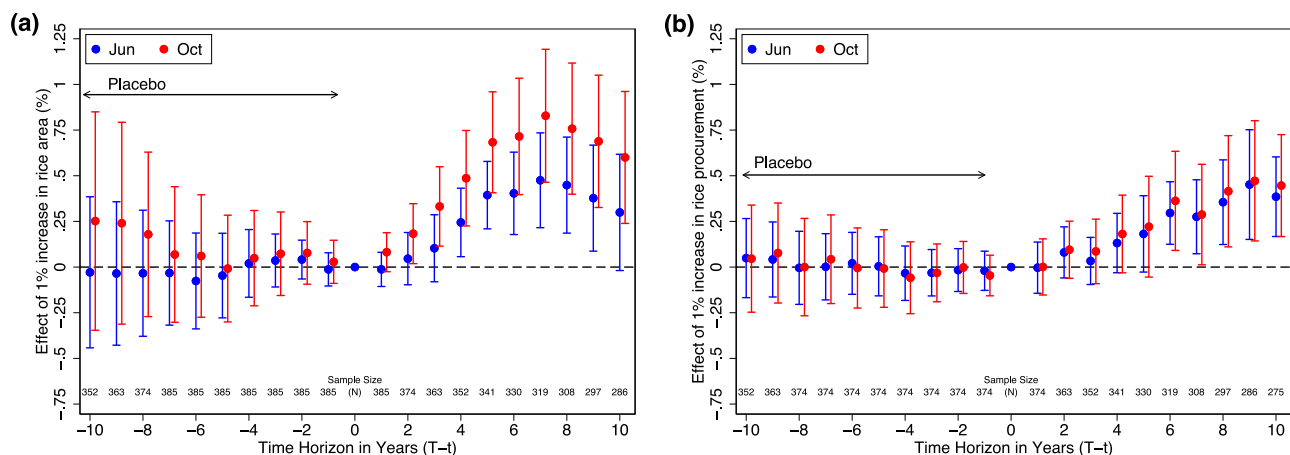
Fig. 3 | Effects of producing and procuring rice on groundwater depth in Punjab: 1981–2015. a The figure plots estimates from a regression of change in groundwater depth on log rice area. The dots plot the regression coefficients (means), and the bars represent the 95% confidence intervals estimated using the Newey-West procedure to account for autocorrelation in the error term over ten-year lags. The unit of observation is a district×year. Each dot is an estimate is from a different regression where the change in groundwater depth has been calculated over a different horizon. For example, the estimate at $T = t + 4$ is from a regression where the dependent variable is the proportional change in groundwater depth

between t and $t + 4$. The sample size (N) of the regressions corresponding to a particular horizon is mentions at the bottom of the figure. The blue estimates measure groundwater changes from well readings taken pre-monsoon (June) and red estimates are from readings taken post-monsoon (October). All regressions include district effects, year effects, district-specific trends, net cropped area, population, cumulative precipitation until date T, and temperature as controls. **b** The figure plots estimate from a regression of change in groundwater depth on log rice procurement (as compared to log rice area in panel a). The interpretation of dots and bars are the same as described for panel a.

our estimates could just be picking up spurious correlations. Even though our regression models include a demanding set of control variables and fixed effects, we also estimate placebo models in which we regress past changes in groundwater depths (between years k < t and t) on current rice area or rice procurement (in year t). All the placebo estimates are not statistically different from zero, supporting the robustness of our analysis.

Finally, it is worth reiterating that due to the output subsidy program, the wheat crop has almost saturated the net cropped area during the rabi cropping season since the 1980s (Fig. S5). As a result, the wheat area remains largely constant post-1981. Lack of temporal variation in wheat area, thus, precludes us from statistically estimating the marginal effects of wheat cultivation or procurement on groundwater, even though a majority of Punjab grows wheat and extensively uses groundwater to irrigate the crop.

Case study II: Madhya Pradesh
Historically, the government agencies in Madhya Pradesh did not procure either wheat or rice even when market prices fell below the MSP. But from 2008, the state announced a bonus on top of the national MSP and substantially expanded its procurement operations of wheat. The potency of the output subsidy policy is driven in large part by the procurement machinery of the state at the local level. With strong procurement, the policy became highly active in Madhya Pradesh. Before 2007, the largest volume purchased by state agencies in any year was 0.54 million tons (mt). In 2007 procurement was a mere 0.057 mt. In 2008, this exponentially jumped to 2.4 mt—a 40-fold increase[34].

The policy was introduced when state elections were due later in the year. Procurement operations were also more concentrated in districts that were key producers of wheat. Thus, there was widespread belief that this was an election year gift, and therefore, the farmers did not immediately increase wheat cultivation[34]. Over time, however, as wheat procurement became a fixture in subsequent seasons and spread to other districts, this belief was shed and along with procurement there was also a concomitant increase in area under wheat cultivation (Fig. 4a). Between 2000 and 2007, the area under wheat

cultivation grew at 3% annually, which almost doubled to 5.8% per year between 2008 and 2015.

Some of the growth in wheat area between 2000 and 2008 can be attributed to the improvements in irrigation systems (reliable power for tubewells and completion of canal irrigation projects) that were being made by the state government beginning in early 2000[35]. However, the increased wheat cultivation because of the procurement policy put additional pressure on irrigation demand. The average annual growth in wheat irrigated area was 6.5% between 1991 and 2007 but after 2008, the wheat irrigated area began to increase by 7.9% each year. As was the case in Punjab, much of the new irrigation came from groundwater (wells and tubewells) rather than surface water (Fig. 4b). This change seems to be gradually increasing groundwater stress, although magnitudes are comparatively low since this is a relatively new policy as compared to fifty years of procurement operations in Punjab.

Madhya Pradesh is dominated by hard-rock and mixed aquifers where measurement of groundwater stress is not straightforward. Shallow hard-rock aquifers deplete and replete annually and long-term water level trends are less apparent. It is well known that in such aquifers, groundwater stress can increase even though average groundwater depth may not be increasing[9]. A robust measure of groundwater stress in this region is the need for deep tubewells (with depth >70 m). Deep tubewells are expensive and risky to construct. Their failure causes a precipitous decline in the long-term income of the farmers trying to install them[36]. Farmers install deep tubewells when they do not have access to surface water or groundwater at shallower depths. Thus, an increase in the incidence of defunct dug wells, that are shallow, with a concomitant increase in deep tubewells is a reliable indicator of groundwater stress (Fig. 4c).

The phased introduction of procurement operations in this state provides a natural experiment to estimate the causal impact of this policy on groundwater stress. Given the hydrogeology, we use three different metrics to measure groundwater stress: the proportional change in groundwater depth pre-sowing and post-harvest, the fraction of wells that run dry post-wheat harvest, and the construction of deep tubewells.

(a)

(b)

(c)
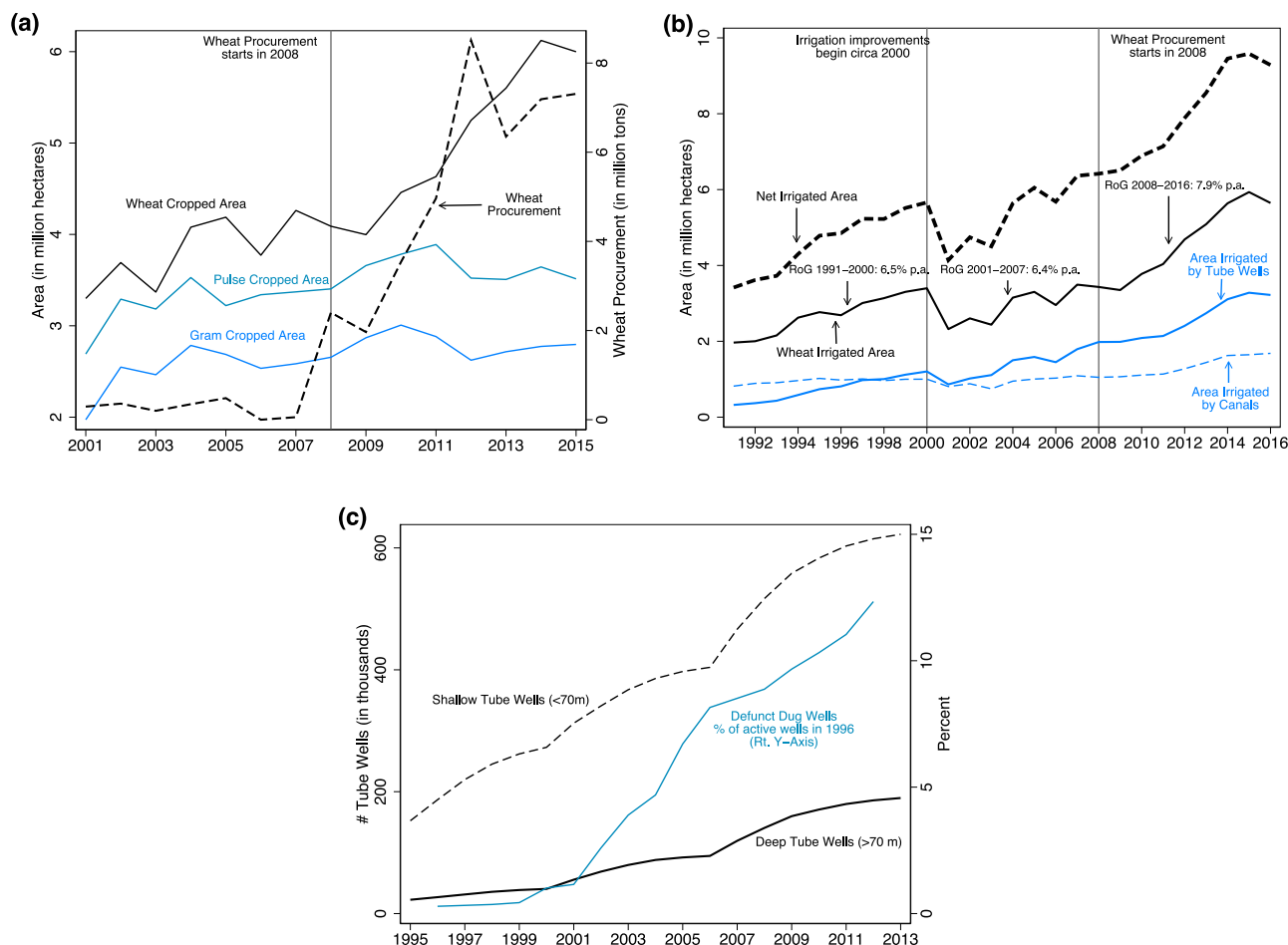
Fig. 4 | Trends in wheat procurement, production, irrigation, and groundwater stress in Madhya Pradesh. a Plots trends in wheat, pulse, and gram cropped area and in quantity of wheat procured by state agencies (right y-axis). **b** Plots trends in net irrigated area, area irrigated by tube wells, area irrigated by canals, and crop area under wheat cultivation that is also irrigated. **c** Plots trends in number of shallow and deep tube wells and defunct wells.

To estimate causal effects, we regress each of these measures on the log of wheat procured and the log of wheat procured interacted with a post-2008 indicator. The unit of observation is a district × year. All specifications include district fixed effects that control for differences in time invariant, district-specific factors that could be correlated with the policy and bias our results. This includes differences in aquifer systems and the fact that procurement started more intensely in districts that already had wheat cultivation and then spread to other districts. We also control for district-specific time-trends that partial out any pre-existing trends in wheat procurement and groundwater stress. Further, we take into account seasonal rainfall and temperature, and for robustness, we also control for total irrigated area in the district. This battery of controls allows us to estimate the causal impact of the policy by comparing groundwater stress in the districts before and after the policy change and relating it to the intensity of procurement operations. The coefficient on the interaction term estimates the causal impact of a 1% increase in wheat procurement on groundwater stress post-2008 as compared to the effect on groundwater in the years before the policy was in place (Methods).

Table 2 shows that pre-policy, the limited wheat procurement that occurred had no relationship with either measure of groundwater stress. Post-2008 however, a doubling of wheat procurement caused a 3.9 pp increase in groundwater level depth (col 1), a 7.6 pp increase in the incidence of dry wells (col 2), and a 4.8% increase in construction of deep tubewells (col 3). All these results consistently show an increase in groundwater stress. The fact that we can triangulate the results across different metrics of groundwater stress increases the reliability

Table 2 | Effects of Wheat Procurement in Madhya Pradesh

	ΔGWL (1)	Dry Wells (prop) (2)	log Deep Tubewells (3)
log Wheat Proc	−0.012	−0.001	−0.000
	(0.022)	(0.008)	(0.010)
	[0.587]	[0.897]	[0.977]
log Wheat Proc × Post-2008	0.039*	0.076***	0.048***
	(0.023)	(0.007)	(0.014)
	[0.097]	[3.0e-13]	[0.001]
N	481	481	407
Clusters	37	37	37
Adj. R^2	0.51	0.27	0.99

Notes: Each observation is a district×year. Robust standard errors clustered at the district level reported in parentheses and associated p-values reported in square brackets. Two-sided t-test used. ΔGWL is the proportional change in groundwater depth between November in year t−1 and May in year t. Dry wells are the fraction of monitoring wells that are dry in the months after wheat harvest (June–September). All regression models include district fixed effects, district specific linear time trends, and controls for temperature and precipitation. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

of our results in this hard-rock aquifer region. Between 2007 and 2016, wheat procurement in Madhya Pradesh increased by almost 70% (from 0.057 mt to 4 mt). Our results therefore suggest that the policy increased the incidence of dry wells by 5.3 pp and the need for deep tubewells by 3.4% during this period. These effects are significant

because they have occurred over a relatively short span of eight years. If wheat procurement continues, groundwater stress in Madhya Pradesh may increase significantly, as seen in Punjab. The statistical model in Table 2, col 1 can be directly compared to the model used for Punjab (Fig. 3b) for a one-year horizon, $\Delta = T - t = 1$.

Why should the marginal effect of wheat procurement vary before and after 2008? This is where the mechanism is crucial. Credible wheat procurement likely incentivizes farmers to grow more wheat over less water-intensive crops, which increases groundwater stress. In Supplementary Information, Table S5, we provide evidence for this core mechanism. We regress log wheat area, log wheat irrigated area, and log area under pulses (the other important crop grown in the state) on lagged log wheat procurement and lagged log wheat procurement interacted with a post-2008 indicator. We use year fixed effects to isolate time-varying aggregate shocks like aggregate supply, price volatility, and climate that could impact procurement and wheat cultivation. We explicitly control for rainfall, temperature, irrigation, and area under other crops for robustness.

Our estimates show that the policy increased the marginal effect of wheat procurement on wheat cultivation in the following year by an additional 13.5% (Supplementary Information Table S5, cols 1–2). A doubling of procurement post-2008 also resulted in a 22% increase in irrigated wheat area due to the policy. Col 4 shows that the increase in wheat area partially came at the cost of a reduction in area under pulses, a less water-intensive crop while Fig. 4a shows that a greater amount of new area also came under wheat cultivation increasing groundwater stress. These intense shifts toward highly irrigated wheat post-2008 leads to differences in the marginal effects pre- and post-2008 in Table 2.

Discussion

In India, agricultural subsidies alone account for about 2–2.5% of GDP[37] while expenditure on productivity improving public goods like agriculture research and infrastructure remains negligible[38]. The design of the subsidy policies is as important as the quantum of subsidies provided. Many nations choose to provide subsidies as income transfers or as insurance against price crashes. These methods are less distortionary. In India, pork barrel considerations have resulted in output subsidies being limited to water-intensive rice and wheat.

The results of this study offer a new understanding of the role that India's output subsidy program and four decades-long assured grain procurement program has played on groundwater stress and highlights important lessons for policymakers focused on designing environmentally sustainable agricultural policies. The results show that subsidy programs have had deleterious consequences for the environment, and sustainability that can have far-reaching consequences.

The thick alluvial aquifers of northern India are a key buffer against climate change-induced weather variability. As their recharge takes centuries, their depletion has exposed India's most productive regions to the possibility of desertification[39–41].

There are other consequences as well. The most important is on nutrition. In the 1960s, India faced food deficiencies. Over time, agricultural policy (output subsidies) has become coupled with food policy (consumption subsidies). The grains procured under the output subsidy program are provided as subsidized food to those with lower income. This is used as a justification to continue with the output subsidy program[42]. While increased cereal productivity that followed the Green Revolution has ensured cereal availability, the diversity in food systems has suffered[43–45]. The Green Revolution crowded out the production of other nutrient-rich crops like coarse cereals and pulses[46,47]. This combined with consumption subsidies made nutrition-rich food relatively more expensive and crowded them out from diets as well[46]. The National Food Security Act of 2013 furthered this by codifying subsidies for staples into law. As a result, the Indian population today faces "hidden hunger" due to nutrition-related deficiencies[47–51].

Finally, there is a trade paradox. India has one of the lowest per-capita availabilities of freshwater reserves. Given such scarce water endowments, economic theory would suggest that the country import water-intensive crops and export the less water-intensive crops. On the contrary, even as taps run dry in major Indian cities, induced by agricultural policy, India exports 25×10^9 m^3 in virtual water every year[52]. Recent estimates suggest that India accounts for 12 percent of the global groundwater depletion that is embedded in international food trade[53]. At this rate, India could lose its entire available water in <1000 years[52].

Policymakers in India should consider rethinking how they provide subsidies to farmers and consumers for securing their own future. Recent research has tried to provide optimal criteria of procurement from the point of view of maximizing nutrition and ensuring food security while saving water resources[54]. However, implementing such criteria will be challenging partly due to limited state capacity. But also, because political economy constraints make any change difficult. The income transfer scheme PM-KISAN is likely to be a good step forward as it is independent of the farmers' crop choice. But presently, it is provided in addition to and not instead of the output subsidy. Governments could consider implementing price deficiency payment (PDP) schemes to compensate farmers for income losses from market volatility, enhancing resilience against climate change. Moreover, as extreme events become more common, investing in new technology is crucial. Thus, policy design should balance direct subsidies with funding for agricultural innovation and research.

More importantly, we must recognize that farmers have a deep mistrust in institutions as coverage of most farmer welfare schemes are far from perfect. In the Green Revolution states of Punjab and Haryana, farmers have relied on the MSP procurement apparatus of rice and wheat for half a century. This is also where the groundwater stress is the most severe. Successfully moving away to alternative systems will require trust-building and convincing farmers that alternative systems of support and subsidies that are not linked to water-intensive crops can work. This is critically important as Indian policymakers vigorously debate the future of these policies as a part of the government's plan to liberalize India's agricultural markets and in reaction to the developments in Ukraine that have affected global wheat markets. They face fierce demands from farmers for even greater support, as fertilizer prices continue to rise.

This study provides cautionary insights into the potential impacts of distortionary agricultural policy on freshwater resources globally. Each year around USD 456 billion is provided as support to agricultural producers in the world and a majority is through measures that are considered distortionary[55–57]. Given the magnitude of resources devoted to agricultural subsidies across the world, understanding their unintended consequences on environmental outcomes remains critical for policymakers to design sustainable, fair, and efficient agricultural policies.

Furthermore, as groundwater is an important resource for the achievement of the UN Sustainable Development Agenda for 2030 related to food security (Goal 2), ensuring access to water for all (Goal 6) and combating climate change (Goal 13), the role of policy in increasing groundwater stress warrants further scrutiny. As the study highlights, the relationship between groundwater and some of these SDG targets can be conflicting since the targets for food security including ending hunger and doubling agricultural productivity could have a negative impact on groundwater. At the same time, access to groundwater will remain critical to help buffer output from climatic variability[20,58,59]. Our results, therefore, caution that subsidy programs that accentuate the utilization of groundwater could inadvertently diminish the ability of groundwater to cushion climatic variability over time and in the future[14,58].

Methods

Data

We compiled several different datasets on crop production, area, and irrigation (apportioned district-level data on Indian agriculture from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)), government procurement of rice and wheat (from the Food Corporation of India and state agencies such as the State Civil Supplies Corporation), groundwater levels and stress (from the Central Groundwater Board of India and the state groundwater board of Punjab), and construction of tubewells (from minor irrigation census rounds 2–5) at the district level. We constructed district-level weather data by averaging gridded temperature and precipitation data from the Indian Meteorological Department over the growing season of crops.

Data on crop production and area from the ICRISAT database spans the years from 1966 to 2015. Where necessary, maps corresponding to 1966 district boundaries are used so that districts and states that split after 1966 are considered together to allow comparability over time.

District-level procurement data for India is generally not available. We were able to obtain this data for two states, Punjab and Madhya Pradesh. For Punjab, district-level data spans the years from 1981 to 2018, and for Madhya Pradesh from the years 2002 to 2016.

Observation well data for the country from 1996 to 2016 was obtained from the Central Groundwater Board of India.

(CGWB) database of monitoring wells, which contains water level measurements recorded four times a year (January, May, August, and November) for 30,311 wells. Of these, 12,837 wells were active in 1996, representing wells with the longest possible records in the database. A separate set of observation well data for Punjab from 1973 to 2003 was obtained from the monitoring wells of the state groundwater board of Punjab, which contains water level measurements on a bi-annual basis (pre- and post-monsoon). Drawdown is measured in observation wells before (June) and after (November) the annual monsoonal recharge season (June– September). It should be noted that water tables reported by monitoring wells may not reflect exactly those reported by farmers in their irrigation wells. Therefore, the averaged water levels at the district level are indicators of water fluctuations rather than absolute value of the water tables actually experienced by farmers. Finally, for our analysis only use dug wells. The deeper wells in the CGWB data are few and thus the estimates are noisy. Since pumping may occur from deeper aquifers in rice growing regions, our estimates reflect lower bound estimates.

Measures of groundwater stress

In addition to averaged groundwater level data at the district level, we use two additional metrics of groundwater stress, namely defunct and dry wells. The literature[9] has shown how missing data in well records carry critical information on groundwater stress that is completely missed in analyzes that routinely filter out this information. Missing data in a well record can occur in two ways: first, the well goes defunct and stops collecting data permanently during the analysis time frame, or second, the well records no data in multiple intermediate months within the time frame. The underlying cause of such missing data can be either physical, where the water level in the well falls permanently or temporarily below the well screen depth, or logistical, where operators neglect maintaining monitoring wells, or they collect or record the data inadequately. Research suggests that the physical change in water level is one of the key underlying reasons for missing data[9]. To overcome the non-random occurrence of missing well data records, two indicators of groundwater stress are used. The percentage of defunct wells is measured at the end of the sample period and is estimated as the proportion of monitoring wells that started collecting data at the beginning of the sample period (active wells) but then permanently stopped collecting data within the sample period. Following the

literature[9], we add the condition that a well should not have recorded data for (at least) the four years preceding the last year in the sample period to be considered defunct. The percentage of dry wells is the proportion of monitoring wells that started data at the beginning of the sample period (active wells) but have missing data and did not record information in the time frame under consideration such as a given season and year. Dry wells could therefore recover in the wet years but lack of water in dry years indicates groundwater stress. Both metrics are indicative of the degree of groundwater stress in the region.

Reasons for using different metrics of groundwater stress in different regions

For a cross-district comparison at the national level we use defunct wells as the metric for groundwater stress rather than groundwater levels because differences in aquifer types make changes in groundwater depth incomparable across regions[9]. Defunct wells or dry wells are a more consistent metric of groundwater stress for comparisons across regions.

Groundwater depth as a measure of stress is the most appropriate for the deep alluvial aquifers of Punjab. where groundwater levels persist and adjust gradually[33]. Here we study changes in groundwater levels over different horizons to assess stress.

Madhya Pradesh predominantly has hard rock and mixed systems that deplete and replete annually. Thus, in these aquifer systems water levels fluctuate greatly but the long-term water level trends are less apparent. Here we use changes in groundwater levels over shorter horizons, combined with the incidence of dry wells and construction of tube wells to assess groundwater stress.

Data constraints and choice of case studies

Studying the role of public procurement in inducing the production of water-intensive crops and quantifying the effect on groundwater stress requires data to satisfy two features. First, we need spatially disaggregated data on procurement and groundwater across India and second, the data must coincide with periods when there is sufficient room for growth in the cultivation of water-intensive crops across different states. In other words, once a cropped area is saturated with water-intensive crops statistical estimation of marginal effects becomes infeasible.

Further caveats. A majority of the CGWB monitoring data are from shallow wells that do not account for the variation due to groundwater pumping from deep aquifers[13]. This limits the analysis given that a majority of groundwater-based irrigation in Punjab is from deeper aquifers. This is corroborated by evidence from satellite-based estimates using GRACE data that show a rapid decline in groundwater storage in comparison to well estimates[13]. However, to the extent that the results still show adverse impacts on groundwater levels after controlling for precipitation and temperature suggests that our estimates are able to capture the impact of subsidies on groundwater stress despite the limitations with using CGWB data. If anything, our estimates represent a conservative approximation of the true effects. More observational data from deep wells across different regions in India would allow for a better representation of groundwater stress due to irrigation.

All-India analysis

Disaggregated district-level data on procurement for most states is not generally available. Thus, for the all-India analysis we only show a cross-sectional association between groundwater stress and cultivation. Moreover, we only use rice cropped area and exclude wheat. This is because groundwater data across regions in India is available only from 1996 and by this time wheat cultivation patterns have stabilized in the country. Wheat area grew at 3.4% each year between 1966–1980

but at a meager 0.7% each year between 1996–2010. Furthermore, wheat is grown in a few districts of only five states (Table S2). As a result, a large number of districts record near zero growth in wheat area and this substantially reduces cross-district variation. Thus, even as wheat producing regions use a lot of groundwater for irrigation, it is infeasible to estimate this statistically.

Since we are restricted to cross-sectional comparisons in our all-India analysis, we view these correlations as motivational.

Case studies

For deeper analysis, we focus on case studies in two states—Punjab and Madhya Pradesh—where we were able to obtain suitable data. Punjab is an important region because this is where the Green Revolution and the procurement policy were first introduced, and it is the region that has faced the highest groundwater stress. Moreover, its thick alluvial aquifers are a key reserve of groundwater and understanding the effects on it are very important from a sustainability perspective.

For this state, we were able to obtain data on procurement and groundwater since 1981. We have groundwater data for two periods—1973–2003 and 1996–2016—from two different sources. The correlation between the two sources for overlapping years is very high (equal to 0.88) and hence we splice them to create one series from 1973–2016. While the area under rice kept growing at a steady rate for about 20 years after 1981, the wheat-cropped area was high but stagnant (Fig. 2c and S5). Hence, for the above-mentioned reasons, we study rice in Punjab between 1981 and 2015.

The wheat crop saturated all of Punjab by 1981 and it covered close to 80% of Punjab net cropped area (Fig. S5). Thus, there was no scope for area under wheat to increase further and it was largely constant in the following years. Lack of time-series variation in wheat area across Punjab and the fact that wheat is grown in very few states disallows a study of the impact of wheat procurement in either the Punjab case study or in the All-India analysis.

To address this limitation, we use a natural experiment in another state of India—Madhya Pradesh. Here, the government suddenly decided to procure wheat in 2008. In 10 years, the state went from procuring no wheat to being the largest procurer of wheat in the country. This exogenous policy-induced shift in cultivation allows us to plausibly estimate the causal effect of the wheat procurement policy on groundwater stress.

Regression models

Punjab. To estimate the effect of rice procurement on production (Table S4) we estimate the following model:

$$\log Q_{d,t} = \beta_0 + \beta_1 \log \text{proc}_{d,t-1} + \mathbf{X}'\gamma + \lambda_d + \lambda_t + \lambda_d t + \varepsilon_{dt}, \quad (1)$$

where Q_{dt} is the rice or wheat production in district d in year t. $\text{proc}_{d,t-1}$ is the procurement of the respective crop in district d in year $t-1$. The vector of controls $\mathbf{X}$ includes precipitation, seasonal temperature and temperature squared in year t and district d. λ_d is a district fixed effect, λ_t a year fixed effect and $\lambda_d t$ is a district-specific linear time trend. In this model, the fixed effects estimator is likely to suffer from Nickell bias[57] as current procurement is mechanically correlated with current cropped area. However, the bias is likely very small because we have 34 years of data (T is very large).

To study the effect of rice production on groundwater in Punjab (Fig. 3a), we estimate the following model:

$$\Delta^T GWL_{dt} = \beta_0 + \beta_1 \log \text{rice area}_{dt} + \mathbf{X}'\gamma + \lambda_d + \lambda_t + \lambda_d t + \varepsilon_{dt}, \quad (2)$$

where $\Delta^T GWL_{dt}$ is the proportional change in groundwater depth in district d between years t and T. rice area$_{dt}$ is the actual area under rice cultivation in district d in year t. The vector of controls $\mathbf{X}$ includes district-year level log net cropped area, log population, cumulative

precipitation until year T, seasonal temperature and temperature squared. λ_d is a district fixed effect, λ_t a year fixed effect and $\lambda_{aez}t$ is a district-specific linear time trend. To estimate the effect of rice procurement on groundwater levels (Fig. 3b) we replace rice area in the above equation with rice procurement.

In both models for statistical inference, we compute Newey–West standard errors to account for serial correlation in shocks over ten years within districts. Robust standard errors clustered at the district level would be preferred since that accounts for arbitrary correlations in error terms. However, the asymptotic properties for inference are not satisfied since Punjab has only eleven districts (small N).

Madhya Pradesh. To estimate the impact of the wheat procurement policy on groundwater stress (Table 2 and S6), we estimate the following model:

$$GWS_{dt} = \beta_0 + \beta_1 \log \text{wheat proc}_{dt} + \beta_2 \log \text{wheat proc}_{dt} \times 1\{t >= 2008\} + \mathbf{X}'\gamma + \lambda_d + \lambda_d t + \varepsilon_{dt}, \quad (3)$$

where GWS_{dt} is a measure of groundwater stress in district d in year t. Groundwater stress is measured as either (a) the proportional change in groundwater level between November in year $t-1$ and May in year t (before sowing and after harvest of the wheat crop), (b) the fraction of wells that are dry post-wheat harvest in June–September year t, or (c) the logarithm of the number of deep wells in district d in year t. wheat proc$_{dt}$ is the quantity of wheat procured in district d in year t. λ_d and $\lambda_d t$ are district fixed effects and district-specific time trends respectively. The vector of controls $\mathbf{X}$ includes seasonal precipitation, temperature, and temperature squared. $1\{t \geq 2008\}$ is a dummy variable taking value 0 for years before 2008 and 1 otherwise. The coefficient β_2 estimates the causal impact of the policy relative to pre-policy effects of wheat procurement. In Table S6, we additionally control for logarithm of total irrigated area.

Finally, to estimate the effect of the wheat procurement policy on production patterns (Table S5), we estimate:

$$\log Y_{dt} = \beta_0 + \beta_1 \log \text{wheat proc}_{d,t-1} + \beta_2 \log \text{wheat proc}_{d,t-1} \times 1\{t >= 2008\} + \mathbf{X}'\gamma + \lambda_t + \varepsilon_{dt}, \quad (4)$$

where Y_{dt} is either wheat area, wheat irrigated area, or pulses area in district d in year t. wheat proc$_{d,t-1}$ is the quantity of wheat procured in disitrict d in year $t-1$. λ_t is a year fixed effect. The vector of controls $\mathbf{X}$ includes seasonal precipitation, temperature, temperature squared, area under other crops, and irrigated area. $1\{t \geq 2008\}$ is a dummy variable taking value 0 for years before 2008 and 1 otherwise. The coefficient β_2 estimates the causal impact of the policy relative to pre-policy effects of wheat procurement.

Here, unlike in model[3], we do not include district fixed effects because after the policy we only have nine years of data. Since contemporaneous procurement and cropped area are mechanically correlated and we do not have a long panel (small T), this would result in Nickell bias[60] and thus in inconsistent estimates. We recognize that our estimates are biased but consistent. Since the goal is to show the mechanism, we feel comfortable with this choice.

For statistical inference in both models, we compute robust standard errors clustered at the district level accounting for an arbitrary correlation in the error terms within districts over time.

Note that in all the regression models 1–4 above, the estimates of the main coefficients of interest (β_1 in models 1–2, and β_2 in models 3–4) may be biased if: (a) there is an omitted factor that has neither been explicitly included in the model nor captured implicitly by the fixed effects, and (b) this omitted factor is correlated with the relevant regressor and potentially influences the dependent variable. For instance, precipitation clearly effects rice and wheat production as well

as groundwater levels. Therefore, not including it as a control variable could bias our estimates of β_1 and β_2. As with any econometric analysis, it is impossible to guarantee that all potential confounding factors have been accounted for. However, our comprehensive set of control variables incorporates the most plausible confounders, such as precipitation, temperature, and population. The fixed effects included in the models also implicitly control for certain unobserved factors. For example, district or AEZ-fixed effects account for hydrogeological characteristics that vary across regions but remain constant over time. Similarly, year-fixed effects control for global time-varying shocks that might affect all districts equally, such as global supply shocks. Given these controls, it is unlikely that our estimates of β_1 or β_2 are biased by confounding factors.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All the data required to replicate the results in this study are available at https://doi.org/10.5281/zenodo.13363059.

Code availability

All the codes for analyzing the data were written in STATA MP 18.5 and are available at https://doi.org/10.5281/zenodo.13363059.

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Author contributions

S.C., R.L., and E.D.Z designed research; S.C. and E.D.Z performed research; S.C. and E.D.Z analyzed data; and S.C., R.L., and E.D.Z wrote the paper. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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