Tradeoffs between crop yield, agricultural residue burning, and groundwater depletion in India's wheat belt

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Classification: Social Sciences - Sustainability Science; Biological Sciences - Agricultural Sciences.

Keywords: wheat yields, residue burning, groundwater depletion, early sowing, India

Abstract: Wheat is a staple crop in India, but yields have stagnated and are projected to further decline due to climate change. One way to increase yields is to ensure timely sowing, which allows the crop to mature prior to damaging heat stress at the end of the growing season. Using novel satellite data products that we developed along with a unique village-level dataset that we collated across India's main wheat belt, the Indo-Gangetic Plains (IGP), we examine the extent of late sowing, its drivers, and the potential tradeoffs of earlier wheat sowing on yield and sustainability outcomes. We find that sowing dates are largely delayed in the eastern IGP, and this is primarily driven by delayed transplanting of the previous rice crop, reduced access to groundwater irrigation, and delayed monsoon onset. Considering tradeoffs, we find that early wheat sowing is associated with higher yields across the IGP, but also with increased groundwater depletion in the western IGP and increased rice residue burning across most of the IGP. We use these results along with maps of where rice residue burning is occurring and where groundwater is over-exploited to identify location-specific interventions that can enhance early wheat sowing sustainably across the IGP. Such actionable information can be used by policy-makers and practitioners to promote the most effective interventions that simultaneously enhance early wheat sowing, increased wheat yields, and environmental sustainability in the world's most populous nation.

Significance Statement: One way to increase wheat yields in India is to ensure the crop is planted on time, yet wheat sowing is delayed over much of India's main wheat belt, the Indo-Gangetic Plains (IGP). We examined the extent of late wheat sowing, its drivers, and the potential tradeoffs of earlier wheat sowing on yield, groundwater depletion, and agricultural residue burning. We find that early wheat sowing can lead to higher wheat yields, especially in the eastern IGP, but this comes at the expense of increased groundwater depletion and more agricultural burning across parts of the IGP. We use this information to identify location-specific interventions that can help promote earlier wheat sowing sustainably across the IGP.

Introduction

Wheat is a critical staple crop that is facing yield stagnation in many regions across the globe (1), largely due to warming temperatures, and yields are expected to further stagnate or decline by mid-century (2). This is especially true in India, where warming temperatures have already decreased wheat yields by 5% and future warming is projected to decrease wheat yields by up to 20% by mid-century (2, 3). This is of concern given that India is the second largest producer of wheat globally (4), and wheat is a staple crop for India's 1.4 billion people, providing up to 40% of household calories (5). Further, wheat demand is projected to increase as India's population grows and per capita wheat consumption increases (6). Actionable solutions are urgently needed that can help India's smallholder farmers increase wheat production in the face of these challenges.

One solution that has been identified through previous field, ground, and modeling work is timely planting of wheat (7, 8). This is because timely planting of wheat allows grain filling, a key growth stage susceptible to high temperatures, to occur prior to heat stress at the end of the wheat growing season in India (7). Yet, despite this benefit, many farmers across the IGP plant their wheat later than optimal. Previous studies, which have largely relied on localized household surveys, have found that one of the biggest determinants of delayed wheat sowing is that the previous season's rice crop is still standing in the field (9–11). This is more likely to occur if monsoon rains are delayed and if farmers do not have access to groundwater irrigation, which allows farmers to transplant rice prior to monsoon onset (12). It is unclear whether these previously identified drivers apply broadly across the IGP, or whether there is regional variation. Yet, identifying potential regional variation in the drivers of late wheat sowing is critical for developing targeted interventions that alleviate the most important constraints in a particular region.

While early sowing has been shown to improve yields (8, 10), it has also been suggested that this may come at the expense of several environmental outcomes. Specifically, groundwater irrigation may help farmers plant their rice and subsequently wheat crop on time, yet, this may not be a sustainable way to enhance earlier wheat sowing in all locations given that over 50% of India's aquifers are already overexploited (13). Simultaneously, one of the fastest ways for farmers to prepare their fields for planting wheat is by clearing the previous rice crop's residues by burning (14). Such agricultural burning has led to widespread increases in air pollution across Northern India, particularly in October to November prior to the sowing of wheat (14, 15). It is therefore critical to understand the tradeoffs between early sowing, groundwater depletion, and rice residue burning across the IGP to better understand where promoting earlier sowing may be a sustainable strategy.

In this study, we create a novel, high-resolution dataset for all villages (n = 171,678) across the IGP to elucidate the relationships between early wheat sowing, wheat yield, rice residue burning, and groundwater depletion. We specifically compile data from novel satellite data products that we have developed on wheat sowing date, wheat yield, and rice transplant date, existing satellite data products on weather and agricultural burning, and village-level census statistics on irrigation and agricultural characteristics to answer four critical questions.

(1) Where is wheat sowing delayed across the IGP?
(2) What are the weather, management, and biophysical factors associated with delayed wheat sowing?

(3) What are the tradeoffs between early wheat sowing and wheat yield, rice residue burning, and groundwater use across the IGP?
(4) Which interventions should be promoted in which locations to enhance early wheat sowing, increase yields, and reduce environmental tradeoffs?

Our study importantly contributes to the literature in three ways. First, our novel village-level dataset allows us to examine relationships between earlier wheat sowing, wheat yield, and environmental outcomes empirically as opposed to relying on models or field-experiment trials which may not represent real-world, on-farm relationships. Second, we examine how these relationships vary across space and reveal potential heterogeneity across the diverse IGP, helping to develop more targeted recommendations. Finally, while some studies have shown the relationship between two of the three variables we examine considering tradeoffs (e.g., groundwater and rice residue burning (14)), no study to date has examined all three outcomes (wheat yield, groundwater depletion, and rice residue burning) simultaneously. Yet, doing so is important to identify the most sustainable solutions to promote earlier wheat sowing across the heterogeneous IGP.

Results

Delayed wheat sowing is concentrated in the eastern IGP and is associated with monsoon onset date, rice transplant date, and irrigation access

We find that wheat sowing dates are largely delayed in the eastern IGP, particularly in the eastern half of Uttar Pradesh and the state of Bihar (Figure 1). Despite this general pattern, there is significant fine-scale variation, with pockets of late sowing in the western IGP (e.g., southern Punjab and western Haryana) and pockets of early sowing in the eastern IGP (e.g., southern Uttar Pradesh).

Considering which management, biophysical, and weather variables are associated with later wheat sowing date, we conducted several analyses. A cross-sectional random forest analysis showed that the variables that most explained variation in wheat sowing date were rice transplant date, monsoon timing (start and end dates), and irrigation access (% irrigation from groundwater wells and distance to canals) (Figure 2). A fixed effects panel regression that used both village and year fixed effects found that wheat sowing date was later when the monsoon started later and rice was transplanted later, except in Uttar Pradesh where a later monsoon onset was associated with an earlier wheat planting date (Table S1). The magnitude of the impact of rice transplant time on wheat sowing date varied across the four states, with larger effects found in the western IGP (Table S1).

Earlier wheat sowing is associated with higher wheat yield, increased crop residue burning, and increased groundwater use

We examined the association between earlier wheat sowing and three important outcome variables: wheat yield, the percent of agricultural area where rice residues were burned, and the amount of groundwater that was used annually. Considering wheat yield, delayed sowing is associated with reductions in wheat yield, particularly when sowing is delayed after November 15th (Figure 3A, Table S2). The magnitude of impact on wheat yield varies across the IGP, with larger negative effects of delayed wheat sowing in the eastern IGP compared to in the western IGP (Figure 3A, Table S2). Values of yield decline range from 0.24% for every day of late sowing in Haryana to 1.10% for every day of late sowing in Uttar Pradesh (Table S2).

Considering rice residue burning, using fixed effects panel regressions with village and year fixed effects, we find that a higher percent of area where rice residues were burned is associated with earlier wheat planting in the western IGP and in Uttar Pradesh, but not in Bihar (Figure 3B, Table S3). The magnitude of this effect varies, with a slightly larger effect on earlier sowing in Uttar Pradesh compared to the Western IGP (Figure 3B, Table S3).

Finally, considering groundwater use, we find that earlier rice transplanting is associated with more groundwater depletion throughout the year in the Western IGP, in the states of Punjab and Haryana (Figure 3C, Table S4). We do not find a significant association between rice transplant date and groundwater depletion in the eastern IGP (Figure 3C, Table S4). It is important to note that our study period covered the time before and after the enactment of the 2009 Preservation of Sub-Soil Water Act, which prohibited the transplanting of rice before mid-June in Punjab and Haryana in order to conserve groundwater. If we restrict our analysis to only those years after 2009, we still see a significant relationship between earlier rice transplanting and increased groundwater depletion in the western IGP (Table S4). To understand whether groundwater depletion was serving as a constraint to earlier wheat planting, we examined the relationship between wheat sowing date and groundwater depth at the start of the wheat growing season using a fixed effects panel regression with village and year fixed effects. We find that deeper groundwater depths are associated with delayed wheat sowing in Punjab and Haryana, suggesting that groundwater access may be serving as a constraint to earlier wheat sowing in this region (Figure 3D, Table S5).

Optimal early sowing interventions vary across the IGP based on sustainability tradeoffs

We use the information from our fixed effects panel regressions (Figure 3) along with information about where wheat sowing is delayed (Figure S1A), where groundwater is critically overexploited (Figure S1B), and/or where rice residue burning is occurring (Figure S1C) to identify optimal early sowing interventions across the IGP at the sub-district scale. We suggest that the regions most optimal for early sowing interventions are those in Bihar (Figure 4A) where wheat sowing dates are the most delayed, groundwater is not currently over-exploited, and we did not find a significant relationship between early sowing and increased rice residue burning. We suggest regions that would benefit from early sowing interventions that also minimize groundwater use (Figure 4B) largely in the western IGP where groundwater is largely overexploited (Figure S1B), though in these locations, sowing dates are not extremely delayed (most fall between November 15 to November 30). For most of the IGP, particularly in Uttar Pradesh, we suggest prioritizing interventions that promote early sowing without increasing the amount of rice residue burning, as these regions were found to have a significant association between early wheat sowing and rice residue burning and have experienced burning during our study period (Figure S1C). Finally, we highlight regions where wheat sowing is already occurring on November 15th or earlier, and where additional interventions for earlier sowing would have less impact (Figure 4D).

Discussion

We examined the extent of late wheat sowing across India's main wheat growing belt, the Indo-Gangetic Plains (IGP), the potential drivers of late sowing, and the tradeoffs between earlier planting and yield and environmental outcomes. We find that sowing dates vary across the IGP, with delayed sowing largely occurring in the eastern states of Uttar Pradesh and Bihar (Figure 1). Considering the potential drivers of late sowing, we find that rice transplant timing is the most or second most important variable across all states (Figure 2), highlighting the need to consider the annual cropping calendar when designing interventions that promote early wheat sowing (10, 11). Specifically, interventions to bring up the sowing date of wheat must consider how the previous rice crop is managed, with cascading effects from one season to the next. Interestingly, we find that the magnitude of impact of rice transplant date on wheat sowing date was larger in the western IGP, potentially because there are fewer other constraints (such as irrigation) compared to in the east (13).

Irrigation and rainfall variables were also found to be important across all states, with percent of irrigation from groundwater to be more important in the west and monsoon start date to be more important in the east (Figure 2). This likely reflects the differences in irrigation type used across the IGP, with more groundwater irrigation from electricity-powered tubewells in the west compared to more canal irrigation from diesel-powered pumps in the east (16). Previous work has suggested that groundwater irrigation allows farmers to transplant their rice crop earlier, and this is associated with earlier wheat sowing in the following season (11, 12). This is because groundwater irrigation, particularly from deep tube wells, is less sensitive to rainfall variability and allows farmers to irrigate even prior to the start of monsoon rains (13). The reduced importance of monsoon onset date in the west may also be partially explained by the passing of the Preservation of Sub-Soil Water Act in Punjab and Haryana in 2009, which does not allow farmers to transplant their rice prior to mid-June (17). Because of this law, planting decisions in the west are less tied to monsoon onset variability as all farmers are required to wait to transplant closer to the time when the monsoon rains typically arrive.

When considering the tradeoffs between wheat sowing date, yield, and environmental outcomes, we find that while there are some consistent effects, the exact tradeoffs and magnitudes vary by state. In the western IGP, in the states of Punjab and Haryana, earlier wheat sowing dates are associated with improved yields (Figure 3A) and more rice residue burning (Figure 3B), and earlier rice transplanting is associated with more groundwater depletion (Figure 3C). This suggests that an earlier annual cropping calendar in the west may be occurring at the expense of multiple environmental outcomes. This is particularly true considering rice residue burning, with high levels of agricultural burned area in Punjab and Haryana (Figure S1C). This region is also experiencing significant groundwater depletion, with most sub-districts facing overexploited groundwater (Figure S1B). Given these challenges and tradeoffs, interventions that promote early sowing in the west should simultaneously promote reduced irrigation use and reduced rice residue burning (Figure 4B and C). There is, however, little delayed sowing in the west, suggesting that early sowing interventions in these locations may not have the most impact compared to other regions in the IGP (Figure 4D).

Considering the eastern IGP, in the states of Uttar Pradesh and Bihar, groundwater is currently not over-exploited (Figure S1B), rice transplant timing does not appear to be driving groundwater depletion (Figure 3C), and it may be possible to increase groundwater use sustainably (12, 18). This is critical given that groundwater irrigation allows farmers to plant rice nurseries and transplant rice prior to monsoon onset, shifting the timing of the annual crop calendar earlier, including wheat sowing date (12). Considering rice residue burning, we see different patterns in Uttar Pradesh and Bihar, with earlier wheat sowing only associated with increased burning in Uttar Pradesh (Figure 3B). This suggests that interventions that promote early wheat sowing in Uttar Pradesh should be mindful of also reducing rice residue burning. While rice residue burning levels are relatively low in the eastern IGP (Figure S1C), they are increasing through time with studies estimating that up to 9-30% of farmers now burn rice residues in the east (19), suggesting that this may become a more important sustainability challenge moving forward. Finally, while we did not find a statistically significant relationship between early wheat sowing and rice residue burning in Bihar, this may be because the MODIS burned area product is not able to detect small and isolated fires well (20). Because of this, we likely missed many burning events across the IGP, particularly in Bihar where field sizes are small and crop management is heterogeneous (21).

Example early wheat sowing and water-saving interventions include direct seeded rice (DSR), where seeds are directly sown into the fields where they will grow for the season, saving both time and irrigation use compared to traditional rice transplanting (22). DSR is also associated with earlier maturation, shifting the time when farmers can plant wheat earlier. Another viable early wheat sowing and water-saving intervention is switching to planting shorter-duration rice varieties, which both require less irrigation throughout the growing season and mature faster, allowing more time for farmers to plant wheat (23). Example early wheat sowing interventions that reduce rice residue burning include the use of the Happy Seeder, which mulches rice residue and then sows wheat seeds directly into the mulch, both reducing the amount of time needed to prepare the wheat field for planting and removing the need to clear rice residues by burning (24). For regions that require early sowing interventions that are both water-saving and reduce burning, any intervention that reduces irrigation use during the monsoon season that also shifts the timing of rice harvest earlier is optimal. Such strategies include both DSR and shifting to shorter-duration rice varieties.

Overall, our study highlights the tradeoffs between earlier wheat sowing and yield, groundwater depletion, and rice residue burning across the IGP. We broadly find that early sowing can lead to yield gains for wheat, particularly in the eastern IGP, but such early sowing is associated with increased groundwater depletion in the west and rice residue burning in most of the IGP. While we suggest several potential early sowing interventions that address sustainability challenges, many of these strategies have not been adopted at scale (25, 26). Future work is critically needed that identifies the most effective ways to promote these interventions to simultaneously achieve increased food production and environmental sustainability in the world's most populous country.

Materials and Methods

Data: We developed and compiled several different datasets at the village-scale for our analysis. These included rice transplant and wheat sowing dates derived using satellite data, wheat yield derived using satellite data, groundwater use data collated from well depth data from thousands of test wells across the IGP, rice residue burned area information extracted from readily-available satellite data products, and a suite of social, economic, and biophysical village-level covariates.

Wheat sowing date and rice transplant date: We used previously developed methods (27, 28) to map crop start of season using MODIS Enhanced Vegetation Index (EVI) time series data. Specifically, we combined the 250 m resolution MOD13Q1 and MYD13Q1 data products to create an 8-day EVI data product from January 2002 to April 2018. We removed cloudy pixels, interpolated missing values, spline smoothed the resulting time series, and identified all inflection points (more details provided in (28)). These inflection points were then used to identify rice transplant and wheat sowing date, defined as the lowest inflection point that occurred during the respective growing season (May 1 to Aug 15 for rice, and October 15 to

January 15 for wheat). MODIS EVI data were downloaded from Google Earth Engine (29) and all additional data processing was done using R Project Software (30). We validated our planting date maps in a previous study (28), where we found that the distribution of our predicted sowing dates matched the distribution of ground truth field-level sowing dates in multiple sites across the IGP. All non-winter cropland was masked using a gridded data product on winter cropped area (27) and all non-wheat cropland was masked by recreating a crop type map produced by the Mahalanobis National Crop Forecast Centre (https://www.ncfc.gov.in/). Mean wheat sowing date and rice transplant date for each year from 2002 to 2017 were extracted for all villages in the IGP using R Project software (30) and village-level boundaries obtained from ML Map Info (https://www.mlinfomap.com/).

Yield: The wheat yield data product was derived in a previous study (28), and was developed using the Scalable Crop Yield Mapper (SCYM) approach (31) applied to Landsat 5, 7, and 8 satellite data (30 m) from 2000 to 2015. The SCYM method uses crop model simulations to create a linear relationship between simulated yield and simulated vegetation indices (VIs), derived from crop model simulations that are parameterized using realistic management variables (31). This linear relationship is then applied to observed VIs from satellite imagery to translate these values into estimates of yield. We bias corrected our satellite yield estimates using district-level census data over the same time period, and found that our model performed well when validated using census data (r ranging from 0.54 to 0.8, details in (28)). Given the moderate frequency of missing pixels due to cloud cover and haze, we were unable to create annual wheat yield maps that provided wall-to-wall coverage. Instead, we developed a mean yield data product that averaged all available yield data from 2000 to 2015 at the pixel scale (28). All analyses were conducted in Google Earth Engine (29). Mean yield value at the village-scale was extracted using R Project Software (30) and village-level boundaries.

Groundwater depth data for test wells: We obtained groundwater depth data from the India-Water Resource Information System (WRIS) from 2002 to 2016 for thousands of test wells from the Central Groundwater Board across the IGP. These data provided mean groundwater level (in meters) of dug wells, bore wells, and tube wells, respectively, during four seasons - pre-monsoon (April - June), monsoon (July - September), post-monsoon (October - December), and mid-winter (January - March). We calculated annual depletion by subtracting the pre-monsoon well depth value in $year_t$ from the pre-monsoon well-depth value in $year_{t+1}$. To maximize data availability, we considered all wells that had at least two measures of annual groundwater depletion throughout the time period. These data were matched to the village dataset by identifying the village that each well was located in using its latitude and longitude location. Village-level matching was done using QGIS and groundwater data processing was done using R Project Software (30).

Agricultural burned area: We calculated the percent agricultural area that was burned during the post-monsoon burning season, spanning from September to December, when rice residues are burned in preparation for planting wheat. We calculated this variable using the Terra and Aqua combined MCD64A1 Version 6.1 MODIS Burned Area data product (32), and masked it to only cropland land cover using the Terra and Aqua combined MODIS Land Cover Type (MCD12Q1) Version 6.1 data product (33). We then calculated the proportion of agricultural area in each village that was burned in each year from 2002 to 2017 during the post-monsoon burning season. All data processing and extraction was conducted using Google Earth Engine (29).

Village-level census covariates: We compiled data from multiple village-level census statistics from different Indian ministries (Table S6, originally compiled and described in 12) and merged these data with village-level shapefiles. Specifically, we obtained socio-demographic variables and percent area that was irrigated by different sources from the Houses, Household Amenities, and Assets census (2011) and the India Demographic census (2001). Distance to the nearest permanent canal was calculated using the nearest distance algorithm in QGIS and a shapefile on global canals produced by the Digital Chart of the World (2009). We derived and extracted several different rainfall variables, including monsoon start date, monsoon end date, and total seasonal precipitation using CHIRPS rainfall data (34) from 2002 to 2017 (Table S6). We also derived and extracted mean winter temperature using the CRU dataset (24, Table S6). All weather data were processed and extracted using Google Earth Engine (29). For soil type, we used the ISRIC soil grids data (36) and extracted the most common soil type at the village-scale for all villages (Table S6) using QGIS software.

Statistical Analyses:

Drivers of delayed wheat sowing: We conducted several analyses to identify the factors most associated with delayed wheat sowing at the state-level. First, we conducted a random forest analysis that examined which socio-economic, demographic, biophysical, crop management, and weather variables (Table S6) most impacted wheat sowing date by identifying those variables that led to the largest percent change in mean squared error (MSE) when dropped from the analysis (Figure 2). All data used to parameterize the model were mean values for each village across the study time period as we did not have time series values for all variables of interest (e.g., socio-demographic variables). For those variables that were found to be important in the random forest analysis and for which we had annual time series data (i.e. monsoon timing variables and rice transplant date), we ran a fixed effects panel regression with village and year fixed effects where wheat sowing date was the dependent variable (Table S1). All analyses were conducted in R Project Software (30).

Tradeoffs between yield, groundwater depletion, and agricultural burning: To estimate the impact of delayed wheat sowing on yield, we ran a cross-sectional regression with wheat yield as the dependent variable, and a suite of factors hypothesized to impact yield, including wheat sowing date (Table S2, Table S6). We also included district fixed effects to account for omitted variables that varied at the district scale. To estimate the effects of agricultural burning on wheat sowing date, we ran a fixed effects panel regression with village and year fixed effects (Table S3). Finally, to estimate the association between cropping decisions and groundwater depletion, we ran two analyses. The first analysis estimated the effect of rice transplant date, wheat sowing date, and seasonal rainfall on the change in groundwater depth over the full annual cycle (premonsoon in $year_t$ to premonsoon in $year_{t+1}$, Table S4). To test whether this relationship held true after the implementation of the Preservation of Sub-Soil Water Act of 2009, we ran the same analysis for all years from 2009 onwards (Table S4). Finally, we estimated the impact of groundwater depth on wheat sowing date decisions by regressing wheat sowing date on the depth to the water table during the time when planting occurs (Table S5). Both groundwater analyses were conducted as fixed effects panel regressions with village and year fixed effects. All analyses were conducted in R Project Software (30).

Prioritization map: We used the beta coefficients of our tradeoffs of interest (Figure 3) along with maps at the sub-district scale of mean winter sowing date (Figure S1A), regions that have critically over-exploited aquifers (Figure S1B, data from (13)), and regions where rice residue burning has occurred over the course of our study (Figure S1C) to identify prioritization regions for early sowing interventions considering sustainability tradeoffs. Regions with delayed wheat sowing but no critically exploited groundwater or significant beta coefficients for residue burning (Figure 3B) are defined as regions optimal for sowing date interventions (Figure 4A). Regions with delayed wheat sowing and critically over-exploited aquifers (Figure S1B) are those where early sowing date interventions should be water-saving considering groundwater use (Figure 4B). Regions with delayed wheat sowing, in states with significant beta coefficients for rice residue burning (Figure 3B), and where some burning has occurred over the course of our study (Figure S1C) are defined as regions where interventions must also consider how to reduce burning (Figure 4C). Finally, we identify regions where wheat sowing already occurs on or before November 15 as those where the impact of additional interventions will be minimal (Figure 4D).

Acknowledgements: We would like to thank Navin Ramankutty for helpful feedback on our analyses, and Brian Weeks for supporting the completion of this article. We also thank several funding sources for supporting the creation of the satellite data products used in this paper, including an NSF SEES Postdoctoral Fellowship (Award Number 1415436), a NASA Land-Cover Land-Use Change Grant (NNX17AH97G), and the NASA new investigator program award (NNX16AI19G) awarded to M. Jain.

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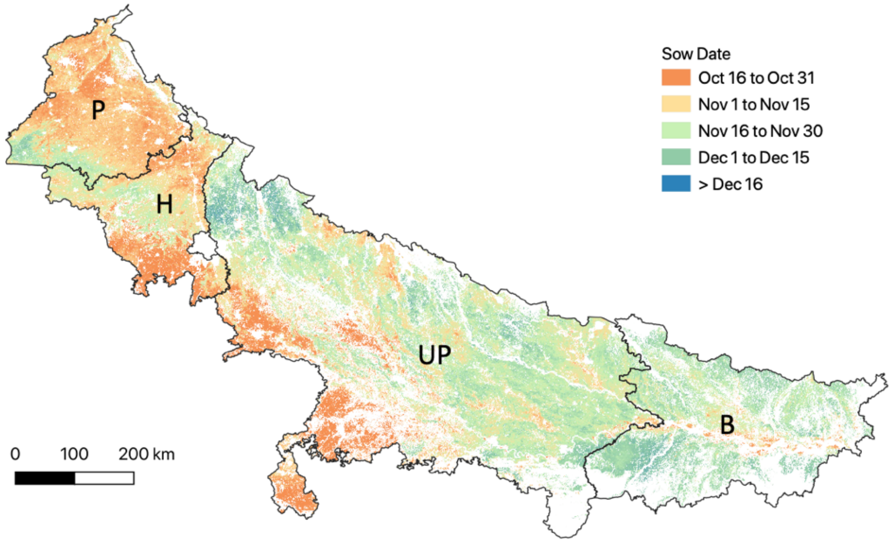

Figure 1. Average wheat sowing date from 2002 to 2017 across the IGP (P = Punjab, H = Haryana, UP = Uttar Pradesh, and B = Bihar) at 250 m resolution. Non-agricultural landcover and non-wheat pixels are masked. Wheat sowing date is largely delayed in the eastern IGP, in the states of Uttar Pradesh and Bihar.

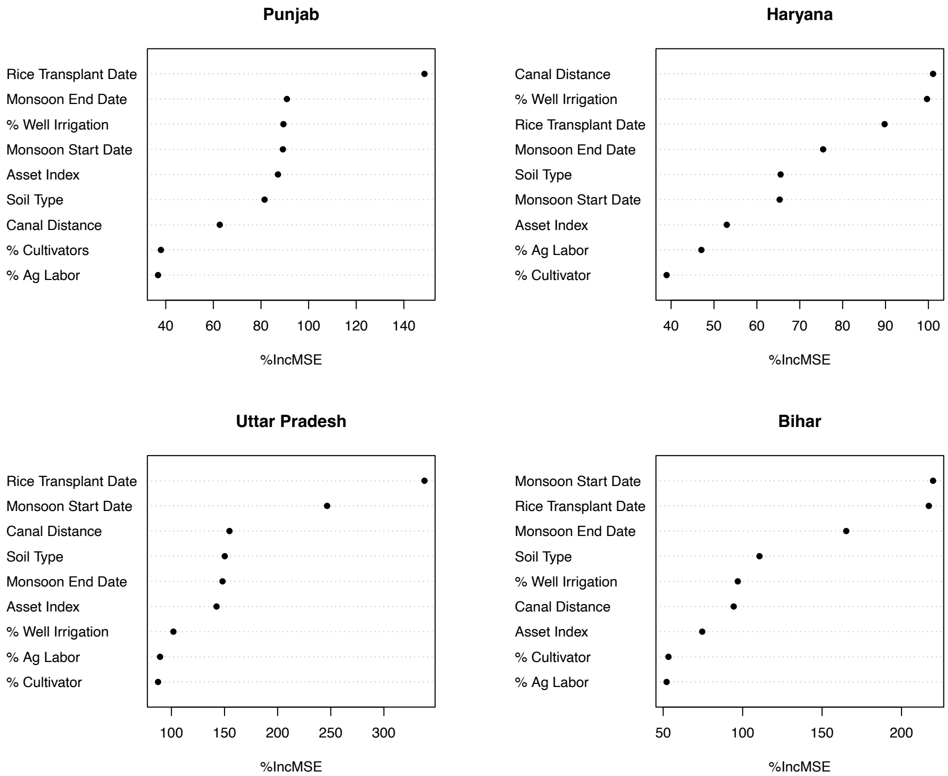

Figure 2. Variable importance plot from a random forest analysis using cross-sectional, village-level data for the four states of the IGP. Variables associated with the largest percent increase in mean squared error (MSE, x axis) when dropped were found to be the variables that contributed most to model fit. In particular, rice transplant time, monsoon timing, and irrigation variables were found to be the most important variables across the region.

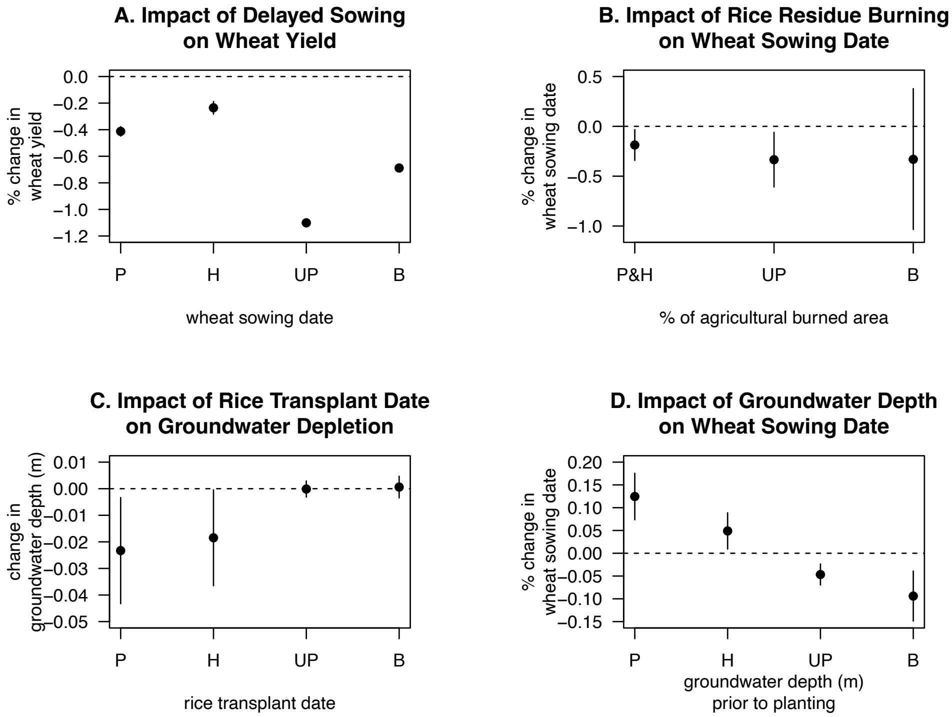

Figure 3. Parameter estimate coefficients for the main variables of interest in our tradeoff analyses. Later wheat sowing dates are associated with reductions in wheat yield across all four states (Panel A). More agricultural area where rice residues are burned is associated with earlier wheat sowing in Punjab and Haryana (modeled together) and Uttar Pradesh, but not in Bihar (Panel B). Later rice transplant dates are associated with less groundwater depletion in Punjab and Haryana, but not in Uttar Pradesh and Bihar (Panel C). Deeper groundwater depths at the start of the wheat growing season are associated with delayed wheat sowing in Punjab and Haryana, but not in Uttar Pradesh and Bihar (Panel D).

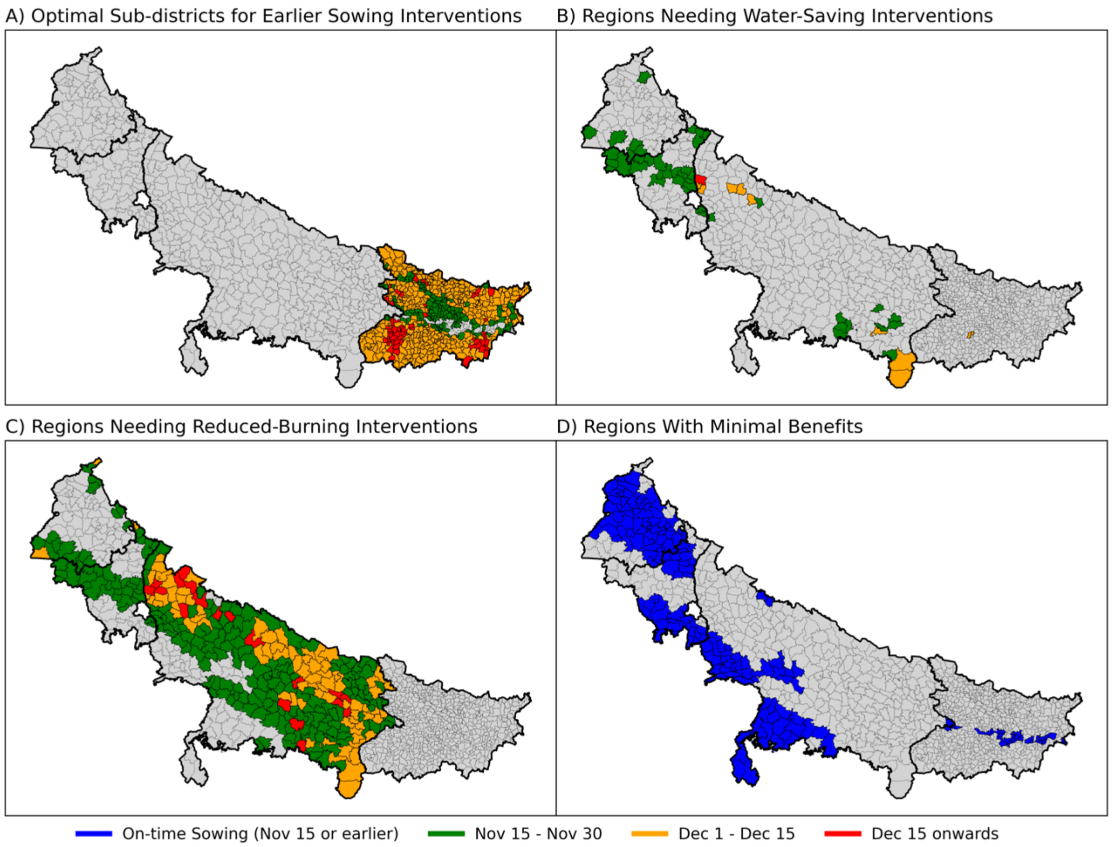

Figure 4. We highlight subdistricts where interventions for enhancing wheat sowing date (A) are optimal due to limited tradeoffs with groundwater depletion and rice residue burning, (B) must also reduce groundwater use, (C) must also minimize rice residue burning, and (D) will have minimal impact as most farmers are already planting on time.

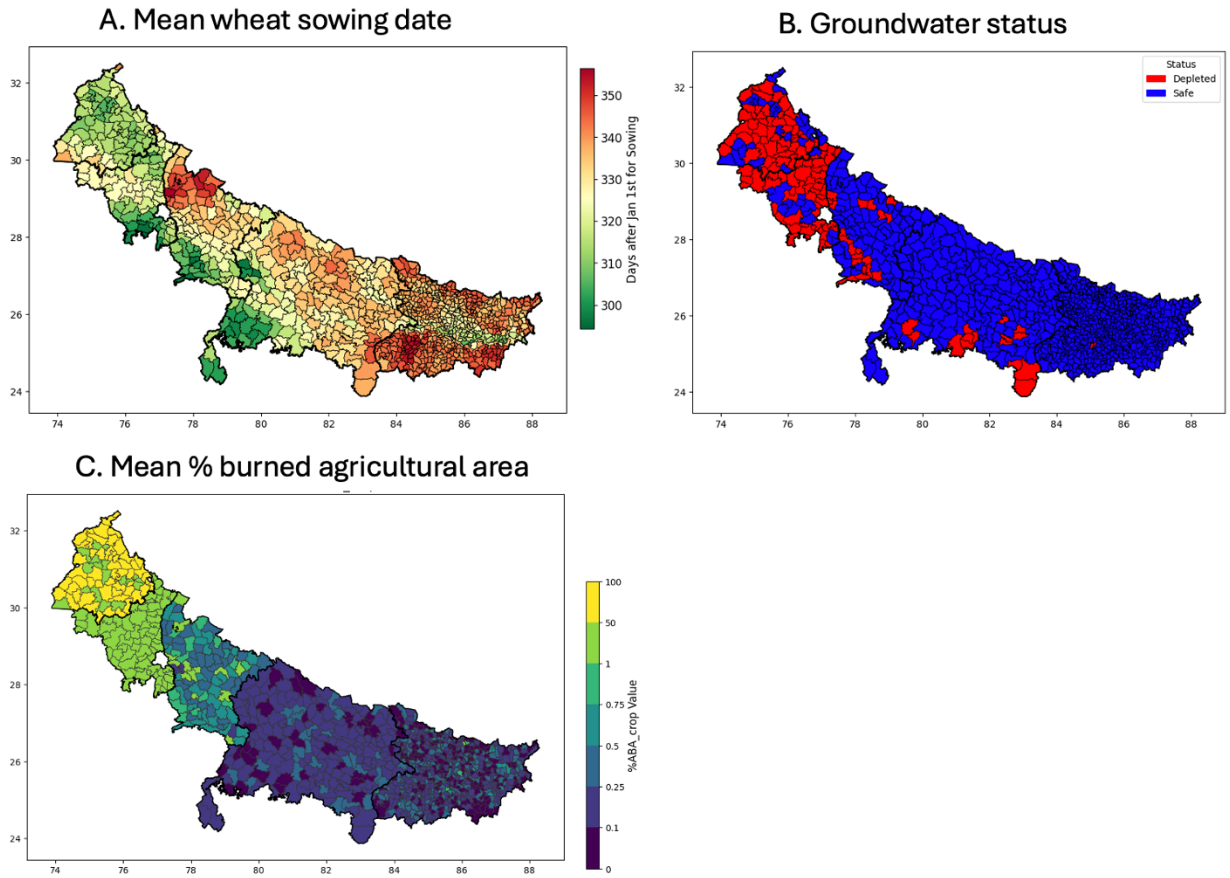

Figure S1. Mean wheat sowing date from 2002 - 2017 at the sub-district scale (Panel A), whether the sub-district has over-exploited groundwater (depleted) or not (safe; Panel B), and mean percent of agricultural area with rice residue burning at the sub-district scale (Panel C).

Table S1. Fixed effects panel regression examining how monsoon and rice transplant timing are associated with wheat sowing date in each of the four states in the IGP. All analyses include village and year fixed effects.

Drivers of Wheat Sow Date

	Wheat sow date			
	Punjab	Haryana	Uttar Pradesh	Bihar
Rice transplant date	0.102***	0.061***	0.027***	0.032***
	(0.003)	(0.002)	(0.0004)	(0.001)
Monsoon start date	0.038***	0.030***	-0.041***	0.037***
	(0.002)	(0.002)	(0.001)	(0.002)
Monsoon end date	0.002	-0.082***	-0.005***	0.016***
	(0.002)	(0.003)	(0.001)	(0.002)
Village FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observations	190,282	103,152	1,545,399	520,818
R^2	0.704	0.835	0.805	0.706
Note:		*p<0.1; **p<0.05; ***p<0.01		

Table S2. Cross-sectional regression that examines the impact of wheat sowing date on yield (log(kg/ha)) after controlling for weather, soil type, irrigation amount and type, socio-economic, and demographic variables at the village-scale for the four states in the IGP. All analyses include district fixed effects to help account for omitted variables at the district-scale. Analyses are done for wheat sowing dates from November 1 onwards and for wheat sowing dates from November 15 onwards.

Impacts of Wheat Sowing Date on Yield

	Log Wheat yield (kg/ha)							
	Punjab Nov 1	Haryana Nov 1	Uttar Pradesh Nov 1	Bihar Nov 1	Punjab Nov 15	Haryana Nov 15	Uttar Pradesh Nov 15	Bihar Nov 15
Wheat sowing date (days)	-0.004***	-0.002***	-0.008***	-0.006***	-0.004***	-0.002***	-0.011***	-0.007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0001)	(0.0001)
Mean winter temperature (C)	0.011***	-0.016***	-0.040***	-0.018***	0.008***	-0.014***	-0.046***	-0.015***
	(0.002)	(0.003)	(0.003)	(0.005)	(0.003)	(0.003)	(0.003)	(0.005)
Total winter rainfall (mm)	-0.0003***	-0.001***	-0.0001	-0.0005	-0.0004***	0.001***	-0.001***	-0.0004
	(0.00004)	(0.0001)	(0.0001)	(0.0003)	(0.0001)	(0.0002)	(0.0001)	(0.0003)
District FE	Y	Y	Y	Y	Y	Y	Y	Y
Soil Type and Irrigation Controls	Y	Y	Y	Y	Y	Y	Y	Y
Socio-economic Controls	Y	Y	Y	Y	Y	Y	Y	Y
Observations	11,165	4,978	89,437	33,523	3,016	2,678	80,821	32,379
R^2	0.652	0.651	0.393	0.306	0.686	0.670	0.422	0.314

Note: *p<0.1; **p<0.05; ***p<0.01

Table S3. Fixed effects panel regression examining the impact of monsoon and rice timing, and the percent of agricultural area with rice residue burning on wheat sowing date (log(kg/ha)) across the states in the IGP. We combined Punjab and Haryana into one analysis given the small sample size of villages with reported burning in a given year. All analyses include village and year fixed effects.

Impact of Agricultural Burned Area on Wheat Sowing Date

	Log Wheat sowing date		
	Punjab, Haryana	Uttar Pradesh	Bihar
% Ag. burned area	-0.002**	-0.003**	-0.003
	(0.001)	(0.001)	(0.004)
Rice transplant date	0.0004***	0.0001***	0.0001***
	(0.00001)	(0.00000)	(0.00000)
Monsoon start date	0.0001***	-0.0001***	0.0001***
	(0.00001)	(0.00000)	(0.00001)
Monsoon end date	-0.0002***	-0.00002***	0.0001***
	(0.00001)	(0.00000)	(0.00001)
Village FE	Y	Y	Y
Year FE	Y	Y	Y
Observations	188,213	1,524,594	514,679
R^2	0.758	0.808	0.704
Note:	*p<0.1; **p<0.05; ***p<0.01		

Table S4. Fixed effects panel regression examining the impact of rice transplant date, wheat sowing date, and seasonal total rainfall on annual groundwater depletion. We do this analysis for the full timeseries, and only for 2009 onwards to represent the period after the Preservation of Sub-Soil Water Act was passed in Punjab and Haryana. All regressions include village and year fixed effects.

Drivers of Groundwater Depletion (m)

	Change in groundwater level (m)							
	Punjab 2002-17	Haryana 2002-17	Uttar Pradesh 2002-17	Bihar 2002-17	Punjab 2009-17	Haryana 2009-17	Uttar Pradesh 2009-17	Bihar 2009-17
Rice transplant date	-0.023*	-0.018*	-0.0001	0.001	-0.031*	-0.044**	-0.001	0.002
	(0.012)	(0.011)	(0.002)	(0.002)	(0.018)	(0.020)	(0.003)	(0.003)
Wheat sowing date	0.004	-0.006	0.004	0.003	0.004	-0.025	0.004	-0.003
	(0.011)	(0.015)	(0.004)	(0.005)	(0.017)	(0.025)	(0.006)	(0.006)
Total monsoon rainfall (mm)	-0.0001	-0.001	-0.001***	-0.0005	0.0004	-0.004**	-0.001***	-0.0005
	(0.001)	(0.001)	(0.0002)	(0.0003)	(0.001)	(0.002)	(0.0003)	(0.0004)
Total winter rainfall (mm)	-0.002	0.009*	0.003	0.002	-0.002	0.004	0.002	-0.003
	(0.003)	(0.005)	(0.002)	(0.005)	(0.004)	(0.007)	(0.002)	(0.006)
Village FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Observations	3,293	4,304	11,137	3,872	2,241	2,573	6,005	2,882
R^2	0.293	0.352	0.193	0.334	0.292	0.429	0.306	0.360

Note: *p<0.1; **p<0.05; ***p<0.01

Table S5. Fixed effects panel regressions examining the impact of groundwater depth at the time of planting and total monsoon rainfall on wheat sowing date across the four states in the IGP. Analyses include village and year fixed effects.

The Impacts of Groundwater Depth on Wheat Sowing Date

	Log wheat sowing date			
	Punjab	Haryana	Uttar Pradesh	Bihar
Groundwater depth (m)	0.001***	0.0004*	-0.0005***	-0.001***
	(0.0003)	(0.0002)	(0.0001)	(0.0004)
Total monsoon rainfall (mm)	0.00001**	-0.00002***	-0.00000*	-0.00002***
	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Village FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Observations	1,419	2,347	8,672	3,228
R^2	0.775	0.837	0.854	0.794
Note:				*p<0.1; **p<0.05; ***p<0.01

Table S6. Table listing the variables included in our regressions, source of variable, formula for calculation (if applicable), and in which analyses they were included.

Type	Variable	Annual	Formula	Source	Analyses
Dependent	Wheat sowing date	Yes	Same algorithm as in (1)	NA	Figure 2, Table S1, Table S3, Table S5
	Yield	No	NA	(1)	Table S2
	Groundwater depletion	Yes	NA	Central Groundwater Board	Table S4
Independent	Rice transplant date	Yes	Same algorithm as in (1)	NA	Figure 2, Table S1, Table S3
	Wheat sowing date	Yes	Same algorithm as in (1)	NA	Table S4
	% Agriculture burned area	Yes	NA	(2, 3)	Table S3
	Well depth start of season	Yes	NA	Central Groundwater Board	Table S5
	Monsoon start date	Yes	First wet day (>1 mm) of first 5-day wet spell (wet spell amount ≥ 38-years wet season mean*5) which is NOT immediately followed by 10-day dry spell with <10 mm	(4)	Figure 2, Table S1, Table S3
	Monsoon end date	Yes	Last wet day (>1 mm) of last 5-day wet spell	(4)	Figure 2, Table S1, Table S3
	Total monsoon rainfall	Yes	Total mm of rainfall from June 1 to Sept. 30	(4)	Table S4, Table S5
	Total winter rainfall	Yes	Total mm of rainfall from Nov 1 to March 31	(4)	Table S2, Table S4
	Mean winter temperature	Yes	Mean temperature (C) from Nov 1 to March 31	(5)	Table S2
Irrigation and soil controls	Canal distance	No	NA	Digital Chart of the World	Figure 2, Table S2

	% Cropland irrigated	No	NA	Household amenities census, (6)	Table S2
	% Irrigation from groundwater	No	NA	Village amenities census, (6)	Figure 2
	Soil type	No	NA	(7)	Figure 2, Table S2
Socio-economic and demographic controls	% Agricultural labor	No	NA	Demographic census, (6)	Figure 2, Table S2
	% Cultivators	No	NA	Demographic census, (6)	Figure 2, Table S2
	% Literate	No	NA	Demographic census, (6)	Table S2
	% Scheduled caste	No	NA	Demographic census, (6)	Table S2
	Asset index	No	NA	Household amenities census, (6)	Figure 2, Table S2

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