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Satellite detection of earlier wheat sowing in India and implications for yield trends

David B. Lobell [a,*], J. Ivan Ortiz-Monasterio [b], Adam M. Sibley [a], V.S. Sohu [c]

[a] Department of Environmental Earth System Science and Program on Food Security and the Environment, Stanford University, Stanford, CA 94305, United States
[b] International Maize and Wheat Improvement Center (CIMMYT), Global Conservation Agriculture Program, Apdo. Postal 6-641, 06600 Mexico DF, Mexico
[c] Department of Plant Breeding & Genetics, Punjab Agricultural University, Ludhiana, India

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ABSTRACT

Wheat is a staple crop throughout much of India, but in many areas it is commonly sown past the optimum window for yields. Recent technologies, such as adoption of no-till practices or earlier maturing cotton and rice varieties, have enabled some farmers to sow wheat earlier, but repeatable and publicly available measurements of sow date trends are lacking. Here we utilize satellite measurements since 2000 to estimate sow dates over a decade throughout wheat growing areas in India. Comparisons with ground-based sow dates in Punjab confirmed the reliability of satellite estimates, and data from two independent satellite sensors were used as a robustness check. We find statistically significant ($p < 0.05$) shifts toward earlier sowing of wheat throughout much of Haryana and Uttar Pradesh, with insignificant changes in Punjab. A production-weighted average of the entire region indicates that, on average, wheat was sown 1 week earlier by 2010 than it was at the beginning of the decade. Using previously published experimental estimates of yield gains from earlier sowing, we estimate that an overall yield gain of at least 5% averaged across India can be explained by the sow date trend. Given that national yield changes since 2000 have been less than 5%, our results indicate that the sow date shift has been a major factor in yield changes over the past decade, and that the net yield effect of all factors other than sow date has been close to zero, perhaps even negative. The results also indicate that sow dates in much of Haryana and western Uttar Pradesh are nearing or already at the optimum window for yields, so that yield benefits from sow date shifts will likely diminish in the next decade.

1. Introduction

Wheat is a major staple in South Asia, a region which continues to have over 300 million malnourished people despite relatively rapid economic growth. Improving wheat yields in the Indo-Gangetic Plains (IGPs) would be a valuable contributor to meeting growing demand for food in the region. However, concerns have mounted over the past decade that wheat yields have stopped rising in experimental trials (Ladha et al., 2003) and in farmers' fields (Chatrath et al., 2007; Lin and Huybers, 2012). Many factors have been cited as explanations for the slowdown in yield growth, including declining soil potassium (Ladha et al., 2003), increased temperatures (Pathak et al., 2003), and increased disease pressures (Sharma et al., 2007).

As a partial solution to yield stagnation, several researchers have proposed that adoption of zero-till or reduced-till (ZRT) management of wheat, whereby drill seeders are used to sow wheat directly into soil, could offer significant yield gains (Mehla et al., 2000; Hobbs, 2001; Hobbs et al., 2008). Currently, much of the planted area of wheat in India is sown after the optimal sowing window because summer crops (typically rice or cotton) have to be harvested and the fields then prepared for wheat sowing. ZRT eliminates this preparation requirement and thus allows sowing as much as 2 weeks before traditional methods in western IGP states, such as Haryana, and nearly a month in eastern IGP states, such as Bihar (Erenstein and Laxmi, 2008). Each day of sowing delay causes roughly 0.8–1.5% yield loss according to field experiments (e.g., Randhawa et al., 1981; Ortiz-Monasterio et al., 1994) and simulation models (Aggarwal and Kalra, 1994), largely because of excessive heat near the end of the season. Thus, adoption of ZRT has shown clear yield gains in cases where it enables wheat sowing closer to the optimum window around mid-November (Erenstein and Laxmi, 2008).

Adoption of ZRT by farmers began in the late 1990s with a roughly exponential increase between 2000 and 2004 (Fig. 1). Official statistics on ZRT area were not collected after 2004 but some recent surveys indicate that net adoption of ZRT has stagnated at roughly 20–25% of total area in survey villages in Northwest IGP (Erenstein, 2009; Singh et al., 2009). However, in recent years there have also been other trends that facilitate earlier planting of wheat, such as the adoption of new cultivars of Bt cotton throughout much of the cotton–wheat region, and increased use of rotavator tillage systems throughout much of the IGP (Erenstein, 2009). Bt

* Corresponding author.
E-mail address: dlobell@stanford.edu (D.B. Lobell).

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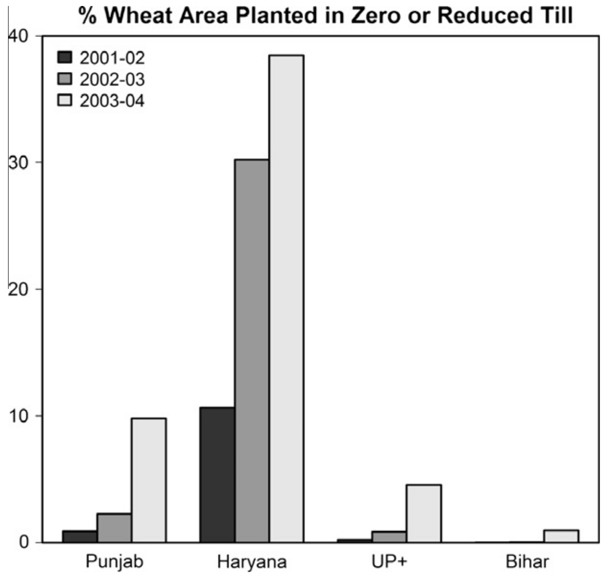

Fig. 1. Percentage of total wheat area planted using zero or reduced till (ZRT) methods, from 2002 to 2004 harvest years (source: Erenstein and Laxmi, 2008).

cotton matures roughly 1 month sooner than traditional cotton varieties, whereas rotavators allow preparation of the field in a single pass that pulverizes the shallow layers of the soil. Both technologies therefore allow earlier sowing of wheat, although they do not possess some of the other benefits of ZRT such as improved soil structure and organic matter accumulation.

Despite selected surveys and anecdotal evidence on adoption of various technologies that affect sow date, little is known about the overall impacts on wheat systems throughout the region. Fortunately, however, just as ZRT rates were increasing at the turn of the century, so too was the ability to monitor vegetation dynamics using satellites. In the current study, we use data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Satellite Pour l'Observation de la Terre Vegetation (SPOT) sensors to measure sow dates on an annual basis since 2000 throughout the Indian section of the IGP. The advantages of using satellite remote sensing in this case include the ability to monitor the entire growing region at low cost, the ability to obtain objective measures of sow dates via repeatable methods, and the lack of any comparable ground-based records on management trends.

Using these satellite datasets, the goals of the study are twofold: (i) to measure and document trends in sow dates throughout the region, which can provide an indirect measure of adoption of new technologies; and (ii) to estimate the effects of these sow date trends on overall wheat yield progress in the past decade. The latter is the main goal of the paper, as understanding the role of sow dates in yield change can help to elucidate the net effect of other factors, such as trends in soil or climatic conditions.

2. Methods

In order to obtain spatially explicit estimates of sow dates across the IGP we used the vegetation index (VI) products from MODIS and SPOT in conjunction with Timesat (Jönsson and Eklundh, 2004). We restrict our analysis to areas of the IGP that regularly cultivate wheat using a global map of wheat harvested area (Monfreda et al., 2008). The harvested area product has a 10′ (roughly 20 km) spatial resolution and gives the percentage of each cell that is cultivated with wheat in the year 2000. We defined our study area as the land within India above 24°N that is also at least 40% cultivated in the Monfreda map (see Fig. 2).

Within this study area both VI products give temporal coverage spanning the years 2000–2010. Our MODIS time series was obtained by combining the MOD13A2 (Terra) and MYD13A2 (Aqua) products (available at https://lpdaac.usgs.gov). Each gives the maximum value of the enhanced VI (EVI) over a 16 day compositing window with an 8 day offset between the two products, yielding EVI estimates at 8 day intervals. The SPOT time series for the same period is composited within a 10 day window and represents a normalized difference VI (NDVI). Both products cover the entire study area at a spatial resolution of 1 km.

The use of MODIS data to estimate plant phenology is well established in the literature. At the global scale, detection of the maximum curvature change rates of fitted logistic functions has been shown to yield good approximations of greenup and maturity onset at broad scales and across vegetation types (Zhang et al., 2006). At finer scales more detailed algorithms have been applied and tested against ground truth data, both in natural ecosystems (Beck et al., 2007) and croplands (Sakamoto et al., 2005). Both of these studies demonstrate reasonable agreement between predictions and validation data at the pixel level as well as unbiased linear relationships between the two, suggesting that greenup and maturity estimates from MODIS VIs would give robust predictions of decadal scale trends at reasonable levels of spatial aggregation. Sakamoto et al. (2010) provide good evidence of the agreement between MODIS derived phenology estimates and metrics of crop development given at the level of agricultural statistical districts by the National Agricultural Statistics Service.

For both VI time series we used Timesat to extract an estimate of sow date. Timesat is a program that provides robust methods of fitting a variety of functions to time series data (Jönsson and Eklundh, 2004). In this study we fit double logistic functions to each time series on a pixel-by-pixel basis. From our fitted functions we were able to extract estimates of the date each year when the green-up phase began; green-up in this study is defined as the point when a fitted curve reaches 10% of that year's maximum amplitude.

The estimates of green-up represent the earliest time that vegetation growth can be reliably detected by satellite, and should be offset from actual sow dates by a fixed number of days related to the time between sowing and emergence. To confirm this, simulations were run with the CERES-Wheat model at a location with a weather station in Northwest India (28.05°N, 77.17°E). Simulations were run for various sow dates for a 9 year period (harvest years 2001–2009) for a field using a cultivar typical of the region and without water or nitrogen stress, given that fields in the study region are irrigated and well-fertilized. The date at which simulated leaf area index (LAI) reached 10% of its maximum value were obtained for each simulation, and plotted against the corresponding sow date (Fig. 3). The green-up date (at 10% of LAI) was highly correlated with the initial sow date ($R^2 = 0.98$), with an average of roughly 3 weeks separating the two dates.

Pixel level estimates of green-up were aggregated on a yearly basis by taking the mean of all the wheat pixels in each district in the IGP. Statewide averages were also computed by taking a weighted average of values in districts, with weights equal to the proportion of average statewide wheat production from each district. An "All India" average was similarly computed from the district-level averages. Although our study only considered districts north of 24°N, only a very small fraction of wheat is produced south of this latitude. For presentation, we focus on trends for three main states (Punjab, Haryana, and Uttar Pradesh (UP)), as well as for the "All India" average.

As mentioned the literature presents reason for confidence in detecting crop phenology. Nonetheless we also sought independent ground-based estimates of sow date for comparison where available. In particular, average sow dates within the state of