



Using satellite remote sensing to understand maize yield gaps in the North China Plain



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ABSTRACT

Substantial gaps have been reported between the average farmer's maize yield and yield potential in China, especially the North China Plain (NCP). This maize yield gap as identified by previous studies indicates large opportunities for raising yield by improving agronomy. Agronomic factors are either transient or persistent. Transient factors, which explain yield differences depending on unpredictable weather conditions, can have significantly different optimums from one year to another. While those transient factors are difficult to improve without reliable forecasts, persistent factors influence yield more consistently and therefore represent the best near-term targets for shrinking yield gaps. In this study, multi-year satellite images are used to quantify field-scale maize yield variation in Quzhou County of NCP, and this variation is then analyzed to determine the role of soil type and persistent management factors in explaining yield gaps. Results indicate that (i) remote sensing can provide reasonably reliable estimates of maize yields in this region; (ii) soil type has a clear effect on maize yields, and one that interacts strongly with growing season rainfall amounts; and (iii) on average roughly 20% of yield differences that appear within any one year are related to factors that persist in other years. Overall, the study presents a generalizable methodology of assessing yield gap as well as the proportion arising from persistent factors using satellite data. Our results suggest that the majority of yield gap is dominated by transient factors, and shrinking this gap may require high quality forecasts to make informed optimal management decisions.

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1. Introduction

There has been increasing demand for maize in China as live-stock and maize processing has become more prevalent. Despite increases in both yield and harvested area over the past six decades, rates of increase in maize yield decreased by 64% during the period of 1990s–2010 in comparison to the period of 1965–1990s (Grassini et al., 2013). In addition to this slowing rate of yield increase, China's economic development in the last three decades has also lead to urbanization and escalating competition for cropland (Lu et al., 2007). With limited potential for expanding crop area, improving maize yield becomes crucial to maintaining and increasing total production.

Multiple studies in China have shown a significant gap between yield potential (Y_p) or water limited yield potential (Y_{wp}) and actual yield (Y_a) (Liang et al., 2011; Wang et al., 2011; Liu et al., 2012; Meng et al., 2013). These studies used either survey or census data to estimate actual yield, and crop model simulation was commonly applied to estimate yield potential. Meng et al. (2013) analyzed

survey data in China that was categorized into four major maize growing regions – Northeast China (NEC), North China Plain (NCP), Northwest China and Southwest China. It was found that according to weighted average in actual yield from 2005–09, the yield gap for irrigated maize and rain-fed maize were 8.6 t/ha (48% of Y_p and 116% of Y_a) and 7.6 t/ha (56% of Y_{wp} and 102% of Y_a), respectively. In a recent review of yield trends around the world, rate of increase in Y_p was found to be higher than Y_a for maize in North, West and Central China over the last 20 years (Grassini et al., 2013). The current highest yield reached in parts of China has already become competitive at international level (Chen et al., 2012), and the average highest recorded yield was as high as 15.4 t/ha, or 93% of simulated Y_p (Meng et al., 2013).

The NCP is particularly critical for national and global maize production, as it produces one-third of all maize in China (Ministry of Agriculture of People's Republic of China, 2009). Yield gap estimates from previous work, using either experimental (Y_e) or simulation-based estimates of yield potential, are summarized in Fig. 1, indicating that yield gains of at least 80% are possible by raising average yields to Y_e or Y_p . Although the gap between crop model simulated Y_p and Y_e shrank over the last 30 years (Wang

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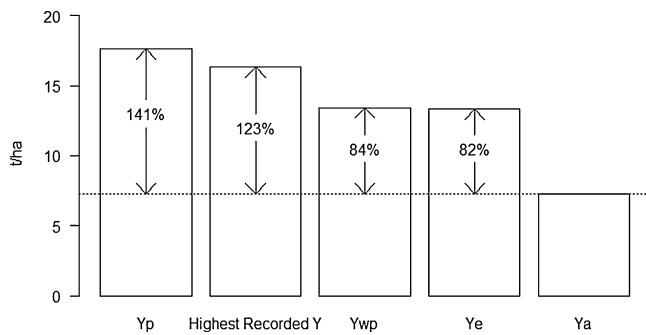


Fig. 1. According to results from Meng et al. (2013), yield gap as a percentage of Y_a in NCP with respect to yield potential (Y_p), water limited yield potential (Y_{wp}), highest recorded yield, experimental yield (Y_e) were 141%, 123%, 84% and 82% respectively. The hybrid-maize simulated Y_p and Y_{wp} took daily step weather data during maize growing season from 2005 to 2009. The highest recorded yields were extracted from previous literature of 2005–2009 time period. The experimental yield (Y_e) was from 18 field experiments in NCP during 2005–2009. The average farmers' yield (Y_a) was estimated according to 2623 farm surveys in NCP during 2007–2008.

et al., 2014), there appears great potential to shrink the exploitable gap ($Y_e - Y_a$) through improving agronomy.

When assessing the prospects for reducing yield gaps, it is useful to distinguish between random and persistent effects of management. Some agronomic factors interact strongly with weather and thus have benefits that are hard to predict or repeat in any single year, such as sowing date in some irrigated wheat systems (Ortiz-Monasterio and Lobell, 2007). In contrast, other factors cause more consistent yield differences and thus offer a more tractable opportunity to shrink yield gaps. Examples of more persistent factors identified in previous work include weed control (Ortiz-Monasterio and Lobell, 2007) and reliability of irrigation deliveries (Lobell and Ortiz-Monasterio, 2008; Lobell et al., 2010; Zwart and Leclerc, 2010). Yield variation in any 1 year is due to both idiosyncratic and persistent factors, and isolating the role of the latter can help to provide a more realistic view of the potential to reduce yield gaps with improved management.

In order to study the level of persistence in yield gap, multiple years of yield data that tracks yield performance of the same fields and encompasses both the highest and the lowest yielding fields are needed. Previous assessments of yield gap in China have mostly relied on one cross-sectional survey to determine actual yield and household level yield variation (Liang et al., 2011; Liu et al., 2012; Meng et al., 2013). Although a sufficiently large sample size could better represent the mean yield of a region, surveys often do not capture the highest and lowest extremes in yield, especially when plot sizes are small. In addition to limited spatial coverage in yield, survey data has limited temporal coverage, as previous survey data of NCP has not surpassed 3 years consecutively. As a result, we need multi-year yield with high spatial resolution that comprehensively covers yield variation in our study area.

Using remote sensing to estimate crop yields fulfills this requirement of spatio-temporal coverage of yield variation. Compared to case studies and field surveys, remote sensing allows yield estimates with better spatial and temporal coverage (Lobell and Ortiz-Monasterio, 2006; Lobell et al., 2007; Schulthess et al., 2013). Earlier studies have utilized remote sensing and Geographic Information System (GIS) soil data to spatially quantify yield potential and yield gap given water limits and soil constraints (Affholder et al., 2013; Oliver and Robertson, 2013). The data coverage advantage of remote sensing is particularly important for studying yield difference persistence in China, where average farmland per household is as low as 0.2 ha as in NCP. Without the assistance of remote sensing, it is hardly plausible to cover large extent of spatial temporal yield variation by conducting surveys.

This study conducted a spatio-temporal analysis of maize yields in Quzhou County of NCP where fields were highly heterogeneous in management practices. We first classified maize fields among all crops grown in the county and estimated yields for each individual year. Then we spatially analyzed these yield estimates to quantify persistent yield gaps for the region overall as well as within individual soil types.

2. Method

2.1. Study site

Our study site is Quzhou County (67,669 ha), which is a typical county in Hebei province of NCP. Located in the center of NCP, Quzhou has flat topography and is crossed by two major rivers. Quzhou has deep alluvial soils which were historically accumulated with salt at great depth. The land was barely arable until 1980s when the saline soil in Quzhou was reclaimed by drilling deep wells to reach fresh water for irrigation and by deepening the drainage ditches for lowering the groundwater table (Shi, 2003). Quzhou County was found in Wang et al. (2011) to represent substantial regions in NCP where Y_a is 67.63–77.35% of Y_p . Cinnamon soil is dominating in the county with alluvial–diluvia parent material. A map of soil texture is shown in Fig. 3. Quzhou's mean annual temperature is 12.5 °C and the average annual precipitation is 489 mm with a standard deviation of 132 mm among years from January 1980 to December 2013. Quzhou has a distinct wet season from late June to late October with 60% of the annual precipitation and a dry season from November to early June in this semi-arid monsoon climate. Average temperature is 17.7 °C in March–May, 21.3 °C in June–August, 14.7 °C in September–November, and 1.30 °C in December–February. Our weather data is from Quzhou meteorological station, which is a point measurement. In this study, we assume that weather conditions are the same across the county, which has little topographic variation.

In Quzhou County, a field is defined by the boundaries of surrounding roads. Each field is carved into strips or parcels of plots to farmers in a village. Those plots do not have visually distinguishable boundaries when cultivating the same crop. Each household owns multiple plots at various locations within the village.

The major crops grown in Quzhou are wheat, maize and cotton. There are a variety of vegetables grown all year long, some of which are grown in greenhouses. We focus on summer maize of this area, which is part of a winter wheat – summer maize crop rotation system. In this system, winter wheat is sown from late September to late October, and is harvested in early to middle of June, after which summer maize is planted (Liang et al., 2011). Maize is harvested in late September, and the leftover crop residual is chopped to return to the ground. As the sow date varies from early June to end of June, the silking date also varies accordingly. In general, silking of summer maize occurs between end of July and early August. The crop calendar of Quzhou County is summarized in Table 1.

Summer maize at Quzhou is partially irrigated and mostly reliant on rainfall. Flood irrigation is available at Quzhou using wells as deep as hundreds of meters, and farmers have little control over when they can irrigate. Many do not sow until irrigation, but some also sow first, expecting their turn of irrigation within a few days.

To analyze the role of soil type in yield variability, we used a soil parent material map from National Soil Survey Data that characterized five soil types (Fig. 3): light loam, medium loam, clay loam, sandy loam, and salt-affected soil, which is high in sulphate and chloride. On saline soil, fields that had adjacent deep wells (200–300 m deep) could irrigate with fresh ground water, but those that had relatively shallow wells would have to use saline water for irrigation.

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