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Assessing the heterogeneity and persistence of farmers' maize yield performance across the North China Plain

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ABSTRACT

The gap between yield potential and average farmers' yield measures the capacity for yield improvement with current technology. The North China Plain (NCP) is a major maize producing region of China, and improving maize yield of NCP is essential to food security of the country. Some previous studies have found a substantial maize yield gap in this region (∼100% of average yields), whereas others have reported much smaller gaps. This study used remote sensing estimated yield at 30-m resolution to quantify county level yield distributions, and then used these distributions to calculate yield gaps and the persistence level of yield for 76 counties in NCP. The average yield was 8.66 t/ha across county years, and the averaged county-level yield gap, as measured by the difference between the top 10 percentile of yields and the average yield of each county, was 0.76 t/ha, or 8.7% of the average yield. When measured as the difference between maximum and average yields in each county, the estimated gap increased to an average of 31%. We also evaluated the persistence level of farmers' yield performance, as an indicator of how much gap might be reduced by propagating agronomic practices of the highest yielding farmers. The average of yield gap persistence was 25.9% of the average yield gap, or 2.3% of average yield with a range from 0.4% to 5.3% across counties. The distance to major rivers was identified as one factor with a significant effect on yield. Nevertheless, there was tremendous spatial heterogeneity in yield persistence level across NCP, and further analysis within individual counties is required to better prioritize means to shrink the yield gap.

1. Introduction

Shrinking the yield difference between highest achievable yield and average yield is essential to improving crop production and maintaining food security amidst rising demand in China, especially from population growth and increasing meat consumption. China represents 19% of the world population and particularly faces this challenge to meet its food demand. Urbanization imposes a threat to the agricultural land area (Shi et al., 2012; Tan et al., 2013; Liu et al., 2014), while yield has become stagnant for major crops in more than 40% of counties in China (Wei et al., 2015). North China Plain (NCP) produces one third of maize in China, so yield progress in this region is particularly important.

Given these concerns, many studies have attempted to estimate average farmers' yield (*Ya*) and potential yield (*Yp*), with the latter defined as the highest achievable yield through ideal management practices given uncontrollable factors, such as weather conditions of a particular location (Lobell et al., 2009). The gap between average and potential yields is an often-used measure of the scope for improving yields with existing technologies. To estimate *Yp*, process-based crop models have been used to simulate the ideal yields for a given set of growing conditions, and alternatively field experiments that try to optimize all management practices to achieve maximum yields have also been used. In an irrigated system, *Yp* can be achieved with sufficient nutrient and water supply so that rainfall and soil conditions are not limiting factors to yield. The model simulated yield potential is lower in a rain-fed (*Ywp*) than an irrigated cropping system(*Yp*) when water supply cannot meet the crop's water demand. Summer maize in NCP, as a part of the summer-maize winter-wheat crop system, is partially irrigated in that irrigation facilities are available but are shared resources so that individual households may not obtain timely access to irrigation (Liang et al., 2011).

Many previous studies have considered the maize yield gap of NCP, most of which used crop model simulated yield as potential — WOFOST in Wang et al. (2011), Hybrid-maize in Meng et al. (2013), APSIM in Wang et al. (2014), and MCWLA-Maize in Tao et al. (2015). The first four of those studies first simulated *Yp* according to

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weather data gathered at experimental stations, and then spatially averaged or interpolated those estimations to a whole region. Tao et al. (2015) simulated *Yp* for each 0.5 by 0.5° grid-point of China and then extrapolated those estimates to county level. The number of experimental stations is limited and may not fully represent the spatial heterogeneity in environmental conditions. Wang et al. (2014) used five experimental stations, and Meng et al. (2013) used yield data from 18 experiments at six experimental stations to represent the NCP region. This type of interpolation and extrapolation may lead to loss of local relevance (van Ittersum et al., 2013). As summarized in Fig. 1a and Table 1, the yield potential estimates differed significantly across those studies, likely in part because of the varied locations represented in space and the innate spatial heterogeneity of NCP.

Similar to the estimation of yield potential, the estimation of actual yield is also susceptible to losing accurate representation of spatial heterogeneity. Previous assessments of maize yield gap in China have mostly relied on one cross-sectional survey or statistics yearbook to determine *Ya* (Liang et al., 2011; Lu and Fan, 2013; Meng et al., 2013). Household surveys are limited in spatial and temporal coverage. Liang et al. (2011) covered six counties in the 2004–2005 growing season only and Meng et al. (2013) used a selection of NCP counties for 2007–2008 season alone. Although yearbook statistics would cover all counties in the region, they failed to manifest the within county variation in yield.

Thus, two key problems exist with prior estimates of yield gap in NCP. First, yield gap estimates of these prior studies varied significantly, casting doubt on the true magnitude of yield gaps (Table 1). With different spatial locations of points and grids for yield potential estimation, different temporal snapshots for gathering actual yield information, and different crop models, there does not appear to be any consensus on the actual magnitude of yield gap in NCP. Second, the underlying causes to the yield gap could not be inferred from these studies. Even though Liang et al. (2011) suggested a few solutions to improving yield in the region, it was unclear which factors were driving the difference between highest and average performing fields given existing technologies.

Both of these shortcomings could be remedied if consistent measures of yields were available across all fields and years. Previous approaches of point-based or gridded interpolation and extrapolation to estimate *Yp* and relying on surveys or statistics yearbook to infer *Ya* neither tracks the same fields' yield nor provides comprehensive spatial coverage. Yet, using remote sensing to estimate crop yields fulfills this requirement of spatio-temporal coverage of yield (Lobell and Ortiz-Monasterio, 2006; Lobell et al., 2007; Schulthess et al., 2013). In this case, yield is estimated comprehensively across space in a region. We adopted an imperical definition of *Yp* as the average of top 10 percentile farmer's yield and *Ya* as the average yield (Lobell, 2013). This yield potential is more reflective of an attainable yield, which is the highest economically viable yield at farmers' current technological level rather than the highest possible yield that could be achieved ignoring the cost of inputs (Neumann et al., 2010). In other words, this defines a potential yield at farmers' current technological level rather than a highest possible yield that maybe achieved through optimizing all conditions regardless of the cost of inputs.

Repeated yield measures can also provide some insight into causes, depending on the consistency of the spatial pattern of yields. If the highest yielding farmers in a single year were consistently achieving the highest yield in other years, then it indicates that something specific to those locations, such as farmer skill, soil quality, or access to water or roads are driving yield gaps. However, if the best performing farmers change from year to year, so that one year's highest yielding fields become average or below average fields in other years, it would follow that shrinking the yield gap is driven by other factors. For example, the best management strategy may change from one year to another depending on unpredictable weather conditions. In that case, simply imitating management practices on the highest performing fields in a specific year may not markedly reduce long-term yield gaps. Thus, studying the persistence level of yield performance deepens our understanding of the potential pathways to shrink yield gaps.

For example, Zhao et al. (2015) used remote sensing estimated yield to track the yield performance of the same fields over five years in Quzhou county of Hebei Province in NCP. Yield gap was empirically defined as the difference between the average and the average top 10 percentile farmer's yield to quantify the yield variation among farmers. It was found that Quzhou had 1 t/ha of yield gap on average, or 10% of the five year average yield, and there was 10% of persistence in yield gap, which meant that 1% of the average yield was persistent yield gap. This number was remarkably small, and it is important to know how representative this county was of the whole NCP region. Similarly, Farmaha et al. (2016) used both ground and satellite-based measures of irrigated maize yield in Nebraska, and found the average persistent yield gap of Nebraska to be 0.6t/ha on average, which was 5% of their average yield.

In this study, we used remote sensing to investigate yield gaps for the entire NCP. Scaling up a remote sensing based analysis from a single county, such as in Zhao et al. (2015), to a whole region requires overcoming both computational and data challenges. NCP has over 200 counties, and even Hebei plain alone has over 100 counties. Processing 30 m resolution data across all counties for multiple years is a substantial computational expense. Fortunately, this constraint has been greatly reduced with the recent development of Google Earth Engine API (GEE). Recent studies have demonstrated the value of GEE for processing large quantities of satellite image data to analyze crop yields (Lobell et al., 2015 Farmaha et al., 2016).

For data constraints, a primary one is the requirement of weather data to obtain yield estimates using existing remote sensing approaches (Zhao et al., 2015; Lobell et al., 2015). While Quzhou had an experimental station since 1980s that was built by China Agricultural University, most other counties in NCP do not have such reliable daily time-step weather data available. Given these constraints, here we proposed using a simplified model based on the average relationships between satellite derived vegetation index (VI) and yields for simulations across a range of locations and years. Unlike Zhao et al. (2015), which ran Hybrid-maize simulations for each year of one county to estimate the linear relationship between VI and yield, we used averaged coefficients from regressions of nine site-year combinations, and applied these to all county-years in major maize growing regions of NCP. We then used the resulting yield estimates to assess both the magnitude and persistence of yield gaps in the region.

2. Method

2.1. Study area

NCP defined in this study includes most of Hebei province that is to the east of Taihang mountain, the western part of Shandong province that is to the west of Tai mountain, and northern part of Henan province that is to the east of the yellow river. This region has a semi-arid monsoon climate with a wet season from late June to late October and a dry season from November to early June. Major Crops grown in NCP include summer maize and winter wheat, cotton, spring maize, and various other vegetables or cash crops.

The extent of our study area was defined by the extent of three Landsat image path rows, from north to south, path 123, row 33; path 123, row 34 and path 123 row 35 (NW corner: 39.8728° N, 114.0744° E, SE corner: 34.9621° N, 117.5759° E). There was a