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# Yield gap analysis of US rice production systems shows opportunities for improvement

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ABSTRACT

Many assessments of crop yield gaps based on comparisons to actual yields suggest grain yields in highly intensified agricultural systems are at or near the maximum yield attainable. However, these estimates can be biased in situations where yields are below full yield potential. Rice yields in the US continue to increase annually, suggesting that rice yields are not near the potential. In the interest of directing future efforts towards areas where improvement is most easily achieved, we estimated yield potential and yield gaps in US rice production systems, which are amongst the highest yielding rice systems globally. Zones around fourteen reference weather stations were created, and represented 87% of total US rice harvested area. Rice yield potential was estimated over a period of 13–15 years within each zone using the ORYZA(v3) crop model. Yield potential ranged from 11.5 to 14.5 Mg ha$^{-1}$, while actual yields varied from 7.4 to 9.6 Mg ha$^{-1}$, or 58–76% of yield potential. Assuming farmers could exploit up to 85% of yield potential, yield gaps ranged from 1.1 to 3.5 Mg ha$^{-1}$. Yield gaps were smallest in northern California and the western rice area of Texas, and largest in the southern rice area of California, southern Louisiana, and northern Arkansas/southern Missouri. Areas with larger yield gaps exhibited greater annual yield increases over the study period (35.7 kg ha$^{-1}$ year$^{-1}$ per Mg yield gap). Adoption of optimum management and hybrid rice varieties over the study period may explain annual yield increases, and may provide a means to further increase production via expanded adoption of current technologies.

## 1. Introduction

The quantification of crop yield potential (the yield possible without constraints from water, nutrients, pest and disease pressure), the attainable yield (the proportion of yield potential attainable by farmers given economic optimization), and the corresponding yield gap (the difference between attainable yield and actual yields) is crucial to meeting the challenge of increasing food, fuel, and fiber production to meet the demands of a growing world population (Lobell et al., 2009; Grassini et al., 2013; Fischer, 2015). Focusing research and policy on areas where improvement is easiest cannot occur without understanding the current state of yield gaps. Recent papers (Licker et al., 2010; Foley et al., 2011; Mueller et al., 2012) suggest several highly intensified agricultural systems have achieved actual yields equivalent to nearly 100% of attainable yield for most staple crops. However, many of these same systems continue to experience yield increases in the last decade, calling into question both the accuracy and suitability of

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*Abbreviations:* CA, California; TX, Texas; AR, Arkansas; MO, Missouri; MS, Mississippi; LA, Louisiana.

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the methodology used by these earlier estimates. For example, US rice yields averaged 7.8 Mg $\text{ha}^{-1}$ in the time period 2009–2011 (US Department of Agriculture - National Agricultural Statistics Service, 2016), yet these papers estimated US rice attainable yield at 7.43 Mg $\text{ha}^{-1}$. Average US rice yields have continued to rise; from 2012 to 2015 US average yields were 8.5 Mg $\text{ha}^{-1}$ (US Department of Agriculture - National Agricultural Statistics Service, 2016). This inaccuracy could be caused by the method used to estimate attainable yield, namely taking the 95% quantile of actual yields as attainable yield. This method has distinct disadvantages; because yield potential is not estimated, in systems where actual yields are well below yield potential, estimated attainable yield may be lower than the true potential.

These inaccurate estimates of crop yield gaps can confound efforts to focus research on where improvements are easiest. Despite comparatively low domestic rice production and consumption, the US is the 4th largest exporter of rice onto the global market (Childs, 2016). This is due in part to the fact that US rice production systems are highly intensified and are amongst the highest yielding rice systems globally (FAOSTAT, 2015). Changing demographics and population growth are expected to increase US domestic consumption (Westcott and Hansen, 2016), while land suitable for production is increasingly constrained by urbanization (Godfray et al., 2010; Foley et al., 2011). Additionally, warming temperatures driven by global climate change are projected to decrease yields (Peng et al., 2004). To maintain its position in the global market, the US must increase production per unit area despite these factors. Failure to do so will threaten food security in areas that rely on rice imports. If US rice production is currently achieving 100% of attainable yield (i.e., the maximum yield given physical and economic limits), research efforts should focus on increasing yield potential through breeding new rice varieties with greater inherent yield potential (e.g., Denison, 2015; Dingkuhn et al., 2015; Sheehy and Mitchell, 2015). If, however, there are some areas not at 100% of yield potential, the challenge can be partially addressed by management. Under this scenario, increasing genetic yield potential should be combined with efforts to realize the current yield potential through optimum management and broader adoption of current yield-increasing technology.

Thus, it is important to revisit yield gaps in US rice production systems using alternate methods to estimate yield potential. Here, rather than estimating yield potential via quantiles of achieved yields (e.g., Licker et al., 2010; Foley et al., 2011; Mueller et al., 2012), yield potential was estimated using simulations from a mechanistic crop model and up-scaled according to the Global Yield Gap Atlas (GYGA) protocol (van Wart et al., 2013; van Bussel et al., 2015). The strengths and weakness of this approach have been well discussed by other authors (Fischer, 2015; van Ittersum et al., 2013; van Wart et al., 2013; van Bussel et al., 2015). This study sought to (1) quantify rice yield gaps in all major areas of US rice production, (2) explore spatial and temporal variation in yields and yield gaps, (3) identify potential environmental constraints to increasing yields, (4) explore potential ways to increase yields using existing varieties (i.e., without new genetic improvements).

## 2. Methods

### 2.1. Climate zones

Yield potential and yield gaps were calculated within 14 zones following previously developed protocols (van Wart et al., 2013; van Bussel et al., 2015). Agro-climatic zones were identified that captured major differences in global agricultural production areas based on accumulated heat units, aridity index, and temperature seasonality. From these agro-climatic zones, six were identified that each included greater than 5% of total US rice harvested area per the MapSPAM raster layer of rice area (You et al., 2016). Additionally, two zones, each with less than 5% US harvested area (both in TX), were added to ensure coverage of all relevant US rice production areas. These eight agro-climatic zones include 92% of US rice production area. For each agro-climatic zone, one or more weather stations were selected after consultation with rice researchers within each state to ensure representation of rice production areas (e.g., not located in city centers, airports, etc.). From this list of weather stations, 14 reference weather stations (RWS) were chosen. Surrounding each RWS, a 100 km zone was created and clipped by agro-climatic zone boundaries. This ensured each RWS was surrounded by a corresponding buffer zone that consisted of a single agro-climatic zone. In cases where two buffer zones overlapped within the same climatic zone, the buffer zones were separated such that the border between buffer zones was equidistant to each RWS. These final 14 zones represent 87% of all US rice harvested area (Fig. 1).

### 2.2. Weather data

Data for each RWS was collected and quality controlled per the previously developed protocol (van Wart et al., 2013; van Bussel et al., 2015) (see Table S1 for locations of RWS and sources of data). For each RWS, weather data were collected from 1999 to 2014 (except LA, which had data starting from 2001). Solar radiation data for all sites was retrieved from the NASA-POWER Agro-climatic database (National Aeronautics and Space Administration, 2016), since few RWS collected these data. Data were checked for extreme or missing values ($T_{min}$, $T_{max}$, vapor pressure, wind speed, and precipitation), which were imputed using linear interpolation. In cases where greater than 10 consecutive days of data were missing, corresponding values from the NASA-POWER Agro-climatic database (National Aeronautics and Space Administration, 2016) were used after correction (see Grassini et al., 2015 for more information on this method). This correction adjusts NASA-POWER data to be closer to locally observed values by estimating the bias between the two sources of data over a historical period. In all cases, missing or questionable data constituted less than 5% of annual measurements.

### 2.3. Estimation of yield potential

Yield potential was estimated using the ORYZA(v3) crop model (Bouman et al., 2001). This model was chosen due to its wide-scale adoption and existing body of work validating it for various rice cropping systems (https://sites.google.com/a/irri.org/oryza2000/publications). Calibration and validation of this model to simulate US rice yield potential for representative high-yielding varieties typical of the types planted in the study area (M-206, a pure-line *japonica* type for CA, and Clearfield XL745, an herbicide-resistant hybrid type for the Southern US) is described in Espe et al. (2016). In order to minimize the influence of variation between simulations, yield potential was simulated for each zone over a 13 (LA sites) or 15 year span and then averaged to estimate the long-run yield potential for each zone.

For each zone, simulations began on the average date when 50% of a region had reached emergence (hereafter emergence date) (Fig. 2). The average emergence date was estimated from average planting dates for each zone (as reported by rice researchers in each state) and the historical relationship between planting dates and emergence dates for each state (US Department of Agriculture - National Agricultural Statistics Service, 2016). For CA, emergence was assumed to be the day after planting since CA growers pre-germinate rice seed prior to aerial planting into a field with standing water. Sensitivity analyses were conducted to assess the impact of

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