Agricultural and Forest Meteorology 259 (2018) 173–183

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

# Rice yield potential, gaps and constraints during the past three decades in a climate-changing Northeast China

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ARTICLE INFO

*Keywords:*
Climate change
ORYZA (v3) crop model
Rice
Yield gaps
Yield constraints
Agroclimatic zones

ABSTRACT

Northeast China (NEC) is one of the most important rice production areas in China, accounting for approximately 15% of its total national rice production, and is one of the regions most vulnerable to global climate change. Knowing crops' potential yields is crucial to understanding comparisons of different cultivars, crops and environments as well as plausible future increases and limits to crop yields. To mitigate the impacts of climate change and enhance food security, investigating yield potential (YP), attainable yield ($YP_A$), nitrogen-limited potential yield ($YP_N$), and actual farmers' yield ($Y_a$) as well as rice yield gaps and their causes in NEC under the climate change background is necessary. In this study, the ORYZA (v3) crop model was calibrated and validated for rice phenology and yields. The validated model was then used to determine YP, $YP_A$ and $YP_N$ values as well as yield gaps caused by nitrogen management factors ($YG_{AN}$) and other agronomic and socioeconomic factors ($YG_{Na}$) for five agroclimatic zones in NEC from 1981 to 2010. The regional area-weighted mean YP levels estimated by the model were 12.9 t $ha^{-1}$ for YP and 11.6 t $ha^{-1}$ for $YP_A$ with decreasing trends and 8.7 t $ha^{-1}$ for $YP_N$ with an increasing tendency. The $Y_a$ was 6.8 t $ha^{-1}$, with a significant increase of 1.1 t $ha^{-1}$ per decade ($p < 0.01$), and farmers achieved 58.6% of the YP. The $YP_A$ accounted for 80.9–94.8% of the YP in NEC. The regional exploitable yield gap ($YG_E$) was 4.8 t $ha^{-1}$. The regional yield gaps were shrinking at 0.47 and 0.88 t $ha^{-1}$ per decade for $YG_{AN}$ and $YG_{Na}$, respectively. In conclusion, because of the persistently large yield gap between farmers and $YP_N$, $YP_A$ provides the government and farmers an opportunity to significantly increase rice production by controlling socioeconomic factors and adopting high-yield agronomic management practices based on site-specific conditions, including optimized irrigation and fertilization practices and "super" rice cultivars.

## 1. Introduction

From 1880 to 2012, the global average temperature has increased by 0.85 °C, and this general warming is especially obvious in the mid- and high-latitude areas of the northern hemisphere (IPCC, 2013). Previous studies have indicated that northeast China (NEC) is one of the areas in China most susceptible to climate change (Yang et al., 2015). The average temperature in NEC increased by 0.38 °C per decade during the past five decades, while the duration of sunshine simultaneously decreased by 42 h per decade (Yang et al., 2015). On the other hand, NEC is an important japonica rice production region, wherein rice production accounts for 53% of the national total japonica rice production (National Bureau of Statistics of China, 2016). The rice planting area accounts for approximately 28% of the total grain crop area in NEC. Hence, NEC plays a vital role in food security in China, and rice yields in NEC have the potential to directly affect Chinese national rice production (Zhang et al., 2014).

Yield potential (YP) is defined as the yield of an adapted crop cultivar when grown in favourable environmental conditions in which water and nutrient supplies are not limited and weeds, pests, diseases and other stresses are effectively controlled (Bhatia et al., 2008; Evans and Fischer, 1999). Hence, the potential yield for a certain cultivar in a

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https://doi.org/10.1016/j.agrformet.2018.04.023
Received 20 January 2018; Received in revised form 23 April 2018; Accepted 30 April 2018
0168-1923/

given location is determined by the characteristics of solar radiation, temperature, soil and plant density (Evans and Fischer, 1999; Grassini et al., 2009; Ittersum and Rabbinge, 1997; Zhao and Yang, 2018). Crops' YPs becomes essential to assessing the comparisons of different cultivars, crops and environments as well as for plausible future increases and limits to crop yields. However, it is difficult for farmers to control non-limiting irrigation and fertilization conditions in the field. Therefore, the concept of attainable yield ($YP_A$) was proposed and discussed by many scientists (Mueller et al., 2012; Liu et al., 2016; Lv et al., 2015). $YP_A$ is the yield achieved by high-yield practices and serves as the meaningful YP level to estimate the exploitation ceiling by farmers in a region (Balasubramanian and Sombilla, 2000). The nitrogen-limited potential yield ($YP_N$) is commonly less than the $YP_A$ and obtained under the traditional farmers' nitrogen management programme (Laborte et al., 2012). Actual farmers' yield ($Y_a$) represents the average farmers' yields in a given target area at a given time and in a given ecosystem. The $Y_a$ in a region is commonly much lower than the $YP_A$ for crops because the latter is simulated under high-yield nitrogen and irrigation management programmes in the absence of pests and diseases (Lobell et al., 2009). The gap between $YP_A$ and $Y_a$ is defined as the exploitable yield gap ($YG_E$). As illustrated in Fig. 1, the $YG_E$ was divided into two components among three yield levels by different constraints. The first yield gap component is between $YP_A$ and $YP_N$ ($YG_{AN}$) and is mainly due to differences in nitrogen fertilizer factors as a result of using traditional inputs or practices by farmers (Ahrens et al., 2010; Matson et al., 1998). $YG_{AN}$ can be narrowed by using improved nitrogen fertilization management practices. The second yield gap component is between $YP_N$ and $Y_a$ ($YG_{Na}$) and is caused by other agronomic and socioeconomic factors. These factors may be some of disease, insect, weed, irrigation management and delayed management practices due to weather or other resource constraints (Laborte et al., 2012; Lobell et al., 2009).

Analysis of YP levels is the basis for interpreting yield gaps and constraints, and many previous researchers have used different methods to estimate potential yields for crops. Considering the limiting factors of climate and soil and many reduced forms, empirical models for example, gradually descending models, agroecological zones (AEZ), and global agroecological zones (GAEZ), have been adopted to analyse crop potential yields in specific environments (Fischer et al., 2002; Jiang et al., 2013). Remote sensing and field experiment methods are also used in potential yield studies (Lobell et al., 2009). Crop growth models have been widely and increasingly used to evaluate crop potential yield (Bouman et al., 2001; Liu et al., 2016; Subash et al., 2012) and can dynamically simulate crop growth, development, and yield under various environmental, cultivar, and agronomy management conditions.

Previous literature has empirically suggested that $YP_A$ accounts for 85% or 70–85% of the YP (Balasubramanian and Sombilla, 2000; van Ittersum et al., 2013; Connor et al., 2011). However, these ratios($YR_{AP}$) were not fixed values or ranges among the different crops and regions. To distinguish $YR_{AP}$ in different NEC regions, the ratio of rice $YP_A$ to YP ($YR_{AP}$) was discussed in this research. To our knowledge, this is the first study to evaluate the rice $YR_{AP}$ in NEC. Also, most yield gap studies use only a single definition of potential yields (Lobell et al., 2009). Few comprehensive studies on rice yield gaps have been conducted in NEC, and moreover, no regional analyses of nitrogen constraints or other agronomic and socioeconomic constraints for rice ecosystems in the context of climate change have been conducted in NEC. For the time being, yield gap constraints limit rice producers from increasing their productivity, and narrowing the yield gap and further increasing rice production are vitally important for ensuring food security in NEC.

The objectives of this study were to (1) evaluate the performance of the ORYZA (v3) crop model (Li et al., 2017) for simulating rice development and yields under potential and nitrogen-limited conditions in NEC; (2) investigate the time-series trends of rice YP, $YP_A$, $YP_N$, and $Y_a$ at both the agroclimatic zone (CZ) level and in the NEC region overall; and (3) quantify the $YR_{AP}$ and rice yield gaps caused by nitrogen factors, other agronomic factors and socioeconomic factors in NEC under the background of a changing climate. In this study, the ORYZA(v3) model, which has been proven to be a useful tool to investigate the potential impacts of climate and nitrogen management on rice yield (Espe et al., 2016; Li et al., 2017), was employed to assess the different annual YP levels for rice cultivars widely cropped from 1981 to 2010.

## 2. Materials and methods

### 2.1. Study region and agroclimatic zones

The study region comprised three provinces in NEC, Heilongjiang (north), Jilin (centre), and Liaoning (south), which are representative of the japonica rice planting regions in China. We selected the counties that had rice cultivation areas larger than 5000 ha consecutively from 2006 to 2010 as the major rice-growing areas (Fig. 2) (Liu et al., 2016).

The three levels of yield potential, $Y_a$, and yield gap values were estimated at the county level and then scaled up to CZs based on the climate similarity. The study region was clustered into five CZs (Fig. 2) by a method defined by Licker et al. (2010) using growing degree day (GDD) data, which are vitally important to rice planting in NEC (Han, 1999). The GDD was calculated as described in Ramankutty et al. (2002) as follows:

$$GDD = \sum_{i=a}^{b} \max(0, T - T_{base}) \quad (1)$$

where T is the daily mean temperature (°C), $T_{base}$ is the base temperature for rice, a and b are the beginning and end dates, respectively, of the rice growing season in the study region. The $T_{base}$ value in this study was 10 °C (Han, 1999), and the period with a daily mean temperature consecutively greater than 10 °C was defined as the rice

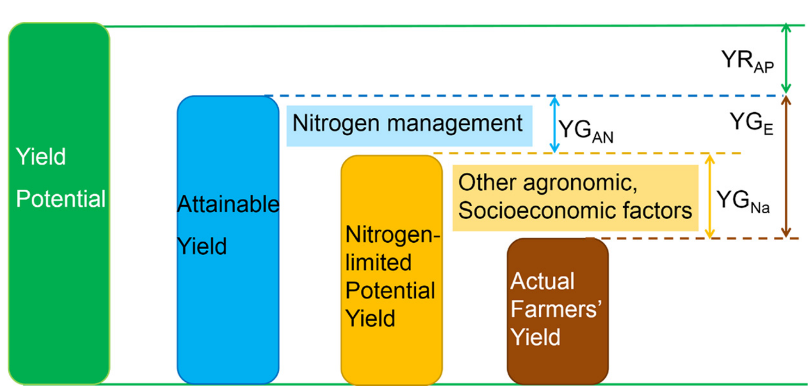


**Fig. 1.** The concept of yield gaps between potential, attainable, nitrogen-limited, and actual farmers' yields and their main constraints.