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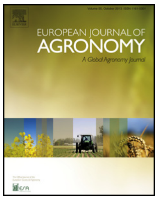

Yield variation of double-rice in response to climate change in Southern China

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ABSTRACT

Food security is a major concern in China due to increasing nutritional demands, limited resources, and a changing and uncertain climate. Rice (*Oryza sativa* L.) plays an important role in food security, whilst its yield is greatly influenced by climate change. Thus, it is critical to quantify changes in rice yield, determine the potential climatic conditions affecting yield variation, and identify strategies to counter the effects of climate change. Historical double-rice yields and climatic variables were analyzed in the major double-rice region of Southern China. Yield varied nonlinearly in most provinces, fluctuated more for late-rice, and exhibited stagnation in 1980–2012. During the growth stages, the mean temperature (T_{mean}) increased significantly at 75.1% of the stations examined ($P < 0.05$), while high inter-annual variation in precipitation (Prec) and radiation (Rad) decreased for 64.2% and 62.2% of stations. The joint effects of the three climatic variables increased yields of early- and late- rice by 0.51% and 2.83%, respectively. Climatic variation accounted for 40.04% and 29.72% of yield variability for early- and late-rice, respectively. Thus, double-rice production in Southern China is strongly affected by inter-annual climatic variation, requiring resilient farming practices to adapt to climate change and consequently enhance food security.

1. Introduction

Agriculture in China has achieved great advances during the past several decades and has successfully fed 22% of the global population with only 7% of all arable agricultural land (Fan et al., 2012). However, several serious problems, such as the increasing population, limited resources, urbanization, and changing climate, are challenging to food security in China (Fan et al., 2012). Owing to yield stagnation and sowing area reductions, total grain yield has only increased 28% from 1980 to 2008 (Liu et al., 2013). In addition, climate change has posed impacts on agricultural production in various regions (Auffhammer et al., 2012; Lobell et al., 2011; Tao and Zhang, 2013; Welch et al., 2010), especially in countries that have not adopted measures to this warming conditions (Wang et al., 2015), and will further exacerbate the food security issues associated with the adverse effects of extreme weather and climatic uncertainty (Lobell et al., 2012; Peng et al., 2004; Ray et al., 2015).

Rice (*Oryza sativa* L.) is a principal staple cereal crop and accounts for ~40% of the total crop production in China (NBSC, 2013). However, due to price fluctuations and unstable profits of double-rice cropping, some farmers have begun to reduce double-rice sowing areas. Downscaling by 3.55 M ha /yr since 1980, compared with 1.56 M ha /yr for total rice, has led to yield reductions in double-rice by 0.79 M t/yr, despite an increase in total rice yield in China (Fig. A1). With the increasing pressure of food security, more and more studies have focused on crop yields trajectory (Ray et al., 2012; Grassini et al., 2013). Previous studies indicated that rice production tended to stagnation in China (Grassini et al., 2013; Wei et al., 2016), which could influence the food security and agricultural sustainability (Wei et al., 2016). Nevertheless, yield trajectory for double-rice in Southern China, has not been fully understood despite of its important role for agriculture production. In addition, global warming, as a hot topic for the past decades, has threatened agriculture production, especially in the last three decades, both statistically and modally (Webber et al., 2015; IPCC, 2014; Ray et al., 2015; Wassmann et al., 2009), and will further aggravate the sensitivity of crop production under uneven changes in climate (Hawkins et al., 2013; Meng et al., 2016). However, rice responses to the warming conditions remain inconsistent. Lobell et al. (2011) estimated a ~3% gain in rice yield in China in the past three decades with the CO_2 fertilizer effect, while Tao et al. (2013) reported regional variations among rice types. Furthermore, some extreme weather conditions, e.g., heat stress, floods, and severe drought, have recently increased in frequency in

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Southern China (CNARCC, 2007), and have consequently affected rice yield and food security (Lesk et al., 2016; Wassmann et al., 2009; Zhang et al., 2016a). However, the yield trajectory for the decreasing area of double-rice in Southern China, and its response to climate change are still unclear, unlike other cereal crops (Zhang and Huang, 2012; Xiong et al., 2013; Zhang et al., 2016b). In addition, the variable effects of normal and extreme climate change have not been settled clearly (Ray et al., 2015). Thus, a comprehensive understanding of yield trajectory for double-rice in China and yield variation caused by climate change will be of great significance for double-rice production. Therefore, it is critical to assess the long-term yield trajectory, quantify the possible contribution of climate change on double-rice yields, and pinpoint responses to historical climate variation. The objectives of this study were to: (i) analyze the trajectory of double-rice yields and the corresponding trends for historical climatic variables in Southern China from 1980 to 2012, (ii) assess the yields dynamic of double-rice due to historical climate changes in Southern China from 1980 to 2012, (iii) determine the predominant climatic models predicting yield variation at the provincial-scale, and (iv) identify adaptive management practices in anticipation of future climate change.

2. Materials and methods

2.1. Study sites and data sources

The study sites were typical double-rice production regions, including Anhui, Hubei, Zhejiang, Jiangxi, Hunan, Fujian, Guangdong, and Guangxi provinces in Southern China (Fig. 1a). Due to a lack of yield records, Jiangsu province was not included. The double-rice yields from the eight provinces produced nearly a third of the total rice yield in China, with a limited sowing area (NBSC, 2013). The regional trajectory in a specific season (early- and, late-rice) was scaled monthly among provincial-scale. The farming calendar for double-rice among these provinces is shown in Fig. 1(c, d), and these data were gathered from the Chinese Agricultural Phenology Atlas (Zhang et al., 1987).

Historical climatic data were obtained from the National Meteorological Information Center, administered by the China Meteorological Administration (CMA, 2014), with a total of 163 stations among the study region. Stations with missing data or limited coverage durations were excluded from the analyses. In total, 135 climatic stations were included in the study with daily data records spanning 1980–2012 (Fig. 1b). Historical daily weather data includes daily mean temperature (T_{mean}), daily minimum temperature (T_{min}), daily maximum temperature (T_{max}), precipitation (Prec), and sunshine duration in hours (Sdh). The Angstrom formula was adopted to convert Sdh to daily solar radiation (Rad) for each station (Black et al., 1954). The general characteristics of climate variables during the double-rice growing seasons at the provincial scale are presented in Table 1. Double-rice yields were collected from the official data of the National Bureau of Statistics of China (NBSC, 2013), these data were sufficient for the analysis, as the data quality has improved by the incorporation of satellite-based land area estimates (Simelton, 2011). The annual average double-rice yield for the eight provinces ranged from 4825.54 (Jiangxi) to 5608.35 kg/ha (Hubei) for early-rice and 4359.84 (Guangxi) to 5895.59 kg/ha (Hunan) for late-rice, and late-rice yield fluctuated more drastically than early-rice yield (Table 1).

2.2. Performances of rice yield and climatic factors

2.2.1. Yield trajectory of double-rice in Southern China

A parsimony-based empirical method including a linear model (LM), quadratic regression model (QM), cubic regression model (CM), stepwise regression model (SWM), and exponential regression model (EXPM) was adopted to determine the yield trajectory in different provinces (Fig. A2). However, the CM was discarded owing to its minute cubic coefficient.

The average yield of double-rice was plotted against year for specific crop regions. All coefficients in these selected models should passed the significant test ($P < 0.05$), and the residual versus year plots for the selected models had no notable trends besides. The coefficient of determination (R^2) and root mean standard error (RMSE) were adopted to check the goodness of fit. A higher R^2 and a lower RMSE in the model were selected before the next step to determine relatively appropriate models. Akaike information criterion (AIC) was used to evaluate the models. Thus, the best models were filtered out. The models are summarized by Eqs. (1)–(5):

$$\text{Linear regression model (LM)} \quad Y_{i,t} = a + b \times t + \varepsilon_{i,t} \tag{1}$$

$$\text{Quadratic regression model (QM)} \quad Y_{i,t} = a + b \times t + c \times t^2 + \varepsilon_{i,t} \tag{2}$$

$$\text{Cubic regression model (CM)} \quad Y_{i\ ,t} = a + b \times \mathrm{t} + c \times t^2 + d \times t^3 + \varepsilon_{i,t} \tag{3}$$

$$\text{Step wise regression (SWM)} \quad Y_{i,t} = \begin{cases} a + b \times t & t \le t_0 \\ a + b \times t_0 + c \times t & t > t_0 \end{cases} \tag{4}$$

$$\text{Exponential regression model (EXPM)} \quad Y_{\mathrm{i},t} = a \times \ 1\text{-}\mathrm{e}^{b \times t} \ + \varepsilon_{i,t} \tag{5}$$

where $Y_{i,t}$ is the recorded yield of double-rice in the region at province i in year t; t_0 in Eq. (4) is the yield-saltation year; a, b, c, and d are coefficients to be fitted.

2.2.2. Climatic factors during the growth seasons of double-rice

A linear regression analysis was used to detect trends in climatic variables in the regions, and the slope of the linear regression was evaluated using Student's *t*-tests at the 95% confidence level.

$$W_{i,t} = a + b \times t \tag{6}$$

2.3. Statistical models

2.3.1. Yield response functions

A widely recognized multiple regression approach was adopted to generate the yield response functions to historical climate trend (Lobell et al., 2011; Tao et al., 2013) as follows:

$$Y_{i,t} = f\left(W_{i,t}\right) \tag{7}$$

$$Y_{i,t} = \alpha + \beta \times t + \chi \times W_{\mathrm{i},t} + \varepsilon_{\mathrm{i},t} \tag{8}$$

W i,t represents recorded data of climatic variables. α, β, χ are the coefficients to be fitted. β is interpreted as the annual benefits from cultivar renewed, technology innovation and other social-economic factors, and χ means the possible impacts by various climate variables.

Predicted climatic variables ($pW_{i,t}$) from Eq. (1) were used for computing the detrended climate.

$$\mathrm{d}W_{i,t} = W_{i,t}\text{-}\mathrm{p}W_{i,t} + W_{i,1980} \tag{9}$$

Where $dW_{i,t}$ is the detrended climatic variables in province i for year t; $W_{i,t}$ and $pW_{i,t}$ are the actual climate and the predicted climate in province i for year t, respectively; $W_{i,1980}$ is the initial climate in province i for year 1980.

The predicted yields with limited changes in climate were computed by using the detrended climatic data (Lobell et al., 2011).