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Research Paper

Potential yield of world maize under global warming based on ARIMA-TR model

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ABSTRACT

With continuous increase of population and demand for nutritional food, analyzing potential yield of world maize affected by global warming is of great significance to direct the crop production in the future. Thus, in this paper both average and top (national) yields of world maize between 2021 and 2030 are projected creatively using ARIMA-TR (Auto-regressive Integrated Moving Average and Trend Regression) model based on historic yields since 1961. The impact of global warming on the yields of world maize from 1961 to 2020 was analyzed using unary regression model. Our study concludes that between 2021 and 2030, average yield of world maize is projected to be from 5989 kg ha^{-1} to 6703 kg ha^{-1} while the top yield from 36530 kg ha^{-1} to 44271 kg ha^{-1}, or the average ranging from 16.39% decreasingly to 15.14% of the top; from 1961 to 2020 global warming exerts positive effect on average yield of world maize less than on the top, which partly drives the gap between these two yields widened gradually; for world maize by 2030, the opportunities for improving global production should be mainly dependent on the advantage of high-yield countries.

Key words: World maize, Potential yield, Global warming, ARIMA-TR model, Top yield

As the most important fodder crop in the world, with continuous increase of population and demand for animal protein consumption worldwide, maize has been attracting researchers' attention for improving its potential yield in the future particularly under global warming. Recent studies on estimating potential yield of maize through modelling have provided a number of important insights as follows. Agricultural Production Systems IMulator (APSIM) model was parameterized and validated to assess the productivity and yield gap of maize in Madhya Pradesh of India (Mohanty et al., 2017), while the APSIM crop model was applied for investigating the interaction between sowing date and cultivar in Khuzestan province of southwestern Iran (Rahimi-Moghaddam et al., 2018). An integrated crop simulation model-satellite imagery method was used for determining the maize yield gap in four major watersheds in Golestan Province of Iran (Pourhadian et al., 2019), while the DSSAT and data assimilation scheme (DSSAT-DA) was used for estimating maize yield and evaluating the sensitivity of maize yield to hydro-climatic variables (Liu et al., 2019), and three crop simulation models (AEZ-FAO, DSSAT-CERES-Maize and APSIM-Maize) were calibrated and evaluated to estimate maize potential and attainable yields in Brazil and to assess the performance of different ensemble strategies to reduce their uncertainties for maize yield prediction (Duarte and Sentelhas, 2019). Martinez et al., (2020) evaluated the impact of temperature and precipitation in 2075 to 2099 on the yield of maize in the Azuero Region in Panama, and predicted a doubled yield attributed to the increase in rainfall, in comparison with the baseline in 1990 to 2003, while using hierarchical linear modeling (HLM) method, Zhu et al., (2021) first predicted maize yield in Jilin Province of China, and got higher accuracy with an adjusted R squared of 0.75, RMSE of 0.94 t ha^{-1}, and normalized RMSE of 9.79% than linear regression (LR) and multiple LR (MLR) methods, and Amiri et al., (2022) evaluated the World Food Studies (WOFOST) model's performance in simulating different field maize (Zea mays L.) growth and productivity variables, using field experimental data of maize growing seasons from 2005 to 2010 in south central Nebraska

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of Iran; and so on.

ARIMA and ARIMAX models have been used to predict the wheat, soybean and sugarcane yield in different parts of the world (Cai et al., 2020; Cai et al., 2021; Pushpa et al., 2022). In this paper, ARIMA-TR (Auto-regressive Integrated Moving Average and Trend Regression) model is creatively used for projecting both average and top (national) yields of world maize between 2021 and 2030.

MATERIALS AND METHODS

Data

Global warming is the most important event in climate change having an influence on the growth and yield of world maize. Therefore, average and top (national) yields of world maize from 1961 to 2020 was used for projecting their futures by 2030, and analyzing their correlations with global mean temperature.

As shown in Fig. 1, from 1961 to 2020: global mean temperature gradually rose in fluctuation; average yield of world maize rose more steadily but slower than the top. 'Average yield' means average yield of world maize worldwide while 'top yield' comes from a specific country whose maize yield countrywide being top in the world in given year as follows: French Guiana in 1961 to 1968; New Zealand in 1969 to 1976, 1979 to 1980, and 1982; Netherlands in 1977 to 1978; Kuwait in 1981, 1988, and 1996; Greece in 1983 to 1984; Israel in 1985 to 1987, 1990, and 2010 to 2011; Qatar in 1989; Saint Vincent and the Grenadines in 2012; United Arab Emirates in 1991, 1993 to 1995, 1997 to 2001, 2004, 2006 to 2009, and 2013 to 2018; and Jordan in 1992, 2002 to 2003, 2005, and 2019 to 2020.

ARIMA-TR model

ARIMA-TR model is the combination of ARIMA (Auto-regressive Integrated Moving Average) model and TR (Trend Regression) model. ARIMA model belongs to time-series approach based on the theory of stochastic process, whose complete representation is mathematically written as formula (1):

$$\left[1-\sum_{i=1}^{p}\phi_i L^i\right](1-L)^d X_t=\left[1+\sum_{i=1}^{q}\theta_i L^i\right]\varepsilon_t \qquad (1)$$

In formula (1), p refers to the number of auto-regressive parameters, while d to the order of differencing required for producing stationarity, q to the number of moving average parameters, t to the time unit, L to the lag operator, $\phi(L)$ to stationary auto-regressive operator, $\theta(L)$ to reversible moving average operator, and $d \in z$ to target variable (Jensen, 1990).

Historic yields of world maize are considered a time-series variable and can be estimated using ARIMA model as it generally rises over time due to continuous improvement of the inputs into its production through scientific and technical means. In application, the projection of world maize yields by 2030 is undertaken following these steps: firstly, to produce logarithmic values of world maize yields from 1961 to 2020 to eliminate the heteroscedasticity, to test the stationarity of time-series and establish 'stationary series' through differencing if not stationary; secondly, to establish such five basic models as ARMA(1,2) model, ARMA(1,1) model, AR(1) model, MA(2) model and MA(1) model to fit world maize yields from 1961 to 2020 and use RMSE for evaluating the fitness; finally, to select optimal basic model used for ARIMA (p,d,q) modelling to project world maize yields between 2021 and 2030.

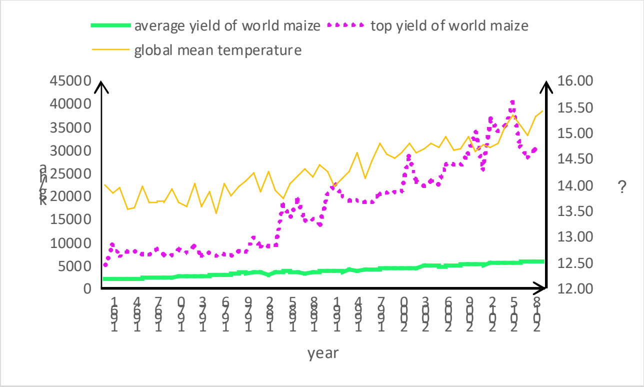

Fig. 1: Global mean temperature (°C), average and top yields (kg ha^{-1}) of world maize from 1961 to 2020. Source:https://www.ncdc.noaa.gov/temp-and-precip/; http://www.fao.org/faostat/en/#data.

In TR model, the year (represented as ordinal number) is treated as the independent while the yield of world maize as the dependent. The model with the highest R squared among such five models as Linear, Exponential, Logarithmic, Polynomial and Power, was used for projecting the futures between 2021 and 2030 basing the projection on historic yields since 1961.

Combing ARIMA model and TR model

Based the comparison between different yields of world maize projected respectively by ARIMA model and TR model, resulting yield was selected following RMSE as estimated result of ARIMA-TR model.

Unary regression model

The impacts of global warming on average and top (national) yields of world maize from 1961 to 2020 were respectively analyzed using unary regression model in which global mean temperature stands for the independent while the yield of crop for the dependent.

RESULTS AND DISCUSSION

Projecting average yields of world maize by 2030 using ARIMA model

The equations of five basic models for fitting average yields of world maize from 1961 to 2020 are established on the basis of their stationary logarithmic series with t-statistic value of -4.90 and critical level of -4.12 value at 1% in ADF unit root test. The RMSE of each basic model used for fitting average yields of world maize from 1961 to 2020 is 325.26 of ARMA (1,2) model, 320.25

of ARMA (1,1) model, 371.70 of AR (1) model, 319.30 of MA (2) model and 318.18 of MA (1) model, respectively. Thus, basic model MA (1) represented as formula (2) is best fitted among five kinds and used for ARIMA (0,0,1) modelling to project average yields of world maize between 2021 and 2030.

$$\ln aym_t = 0.018883 + \varepsilon_t - 0.701507\ \varepsilon_{t-1} \ldots \qquad (2)$$

In formula (2), 'aym' stands for 'average yield of world maize'.

Using the ARIMA(0,0,1) model, average yields of world maize is projected respectively to be 6073 kg ha^{-1} in 2021, 6188 kg ha^{-1} in 2022, 6306 kg ha^{-1} in 2023, 6427 kg ha^{-1} in 2024, 6549 kg ha^{-1} in 2025, 6674 kg ha^{-1} in 2026, 6801 kg ha^{-1} in 2027, 6931 kg ha^{-1} in 2028, 7063 kg ha^{-1} in 2029, and 7198 kg ha^{-1} in 2030, or increased by 18.52% in ensuing decade.

Projecting average yields of world maize by 2030 using TR model

The equation of variation trend for average yields of world maize from 1961 to 2020 is shown as formula (3).

$$y = 0.1784x^2 + 5\ .983x + 1910.2 \qquad (3)$$

As shown in Fig. 1 and formula (3), average yield of world maize from 1961 to 2020 rose in polynomial trend with the highest R squared among the five equations, which is used for projecting the yields between 2021 and 2030 and respectively results in 5989 kg ha^{-1} in 2021, 6067 kg ha^{-1} in 2022, 6145 kg ha^{-1} in 2023, 6224 kg ha^{-1} in 2024, 6303 kg ha^{-1} in 2025, 6382 kg ha^{-1} in 2026, 6462 kg ha^{-1} in 2027, 6542 kg ha^{-1} in 2028, 6622 kg ha^{-1} in 2029, and 6703 kg ha^{-1} in 2030, or an increase by 11.92% in ensuing decade- a lower range of increase than that of ARIMA model.

Average yields of world maize by 2030 estimated by ARIMA-TR model

The RMSE of ARIMA (0,0,1) model used for projecting average yield of world maize between 2021 and 2030 is 318.1835 while that of polynomial TR model is 172.0810. Thus, average yields of world maize between 2021 and 2030 projected using the TR model are selected as the results estimated by ARIMA-TR model.

Projecting top yields of world maize by 2030 using ARIMA model

The variation of top yields of world maize at long term is also deemed as stochastic process. Therefore, top yields of world maize between 2021 and 2030 is projected using ARIMA model basing the projection on historic performance since 1961. The equations of five basic models for fitting top yields of world maize from 1961 to 2020 are established on the basis of their stationary logarithmic series having -4.33 of t-statistic value and -4.12 of critical value at 1% level in ADF unit root test. The RMSE of each basic model used for fitting top yields of world maize from 1961 to 2020 is 4021.94 of ARMA (1,2) model, 4236.99 of ARMA (1,1) model, 4219.82 of AR (1) model, 5939.54 of MA (2) model and 5834.37 of MA (1) model, respectively. Thus, basic model ARMA (1,2) best fitted among the five models and represented as formula (4), is used for ARIMA (1,0,2) modelling to project top yields of world maize between 2021 and 2030.

$$\ln tym_t = 0.024015 + 0.492631 \ln tym_{t-1} + 0.507369 \ln tym_{t-2} + \varepsilon_t + 0.018234\varepsilon_{t-1} - 0.187650\varepsilon_{t-2} \qquad (4)$$

In formula (4), 'tym' stands for 'top yield of world maize'.

Using the ARIMA(1,0,2) model, top yields of world maize is projected respectively to be 31600 kg ha^{-1} in 2021, 32400 kg ha^{-1} in 2022, 33100 kg ha^{-1} in 2023, 33900 kg ha^{-1} in 2024, 34800 kg ha^{-1} in 2025, 35600 kg ha^{-1} in 2026, 36500 kg ha^{-1} in 2027, 37400 kg ha^{-1} in 2028, 38300 kg ha^{-1} in 2029, and 39200 kg ha^{-1} in 2030, or increased by 24.05% in ensuing decade, which shows a larger range of increase than the average yield.

Projecting top yields of world maize by 2030 using TR model

Likewise, the equation of variation trend for top yields of world maize from 1961 to 2020 is shown as formula (5).

$$y = 4.9406x^2 + 212.8\ \ x + 5163.6 \qquad (5)$$

As shown in Fig. 1 and formula (5), top yield of world maize rises also in polynomial trend with top R squared among five kinds, which is used for projecting the yields between 2021 and 2030 and respectively results in 36530 kg ha^{-1} in 2021, 37531 kg ha^{-1} in 2022, 38181 kg ha^{-1} in 2023, 39021 kg ha^{-1} in 2024, 39872 kg ha^{-1} in 2025, 40732 kg·ha-1 in 2026, 41602 kg ha^{-1} in 2027, 42481 kg ha^{-1} in 2028, 43371 kg ha^{-1} in 2029, and 44271 kg ha^{-1} in 2030, or an increase by 21.19% in ensuing decade- a lower range than that of ARIMA model.

Top yields of world maize by 2030 estimated by ARIMA-TR model

The RMSE of ARIMA (1,0,2) model used for projecting top yield of world maize between 2021 and 2030 is 4021.94 while that of the polynomial TR model is 2982.14. Thus, top yields of world maize between 2021 and 2030 projected using the TR model are selected as the result estimated by ARIMA-TR model.

Gap between average and top yields of world maize in 1961 to 2020 and 2030

Based on the results of average and top yields of world maize estimated by above ARIMA-TR models, the gap between these two yield-kinds in 1961 to 2020 and to 2030 is evaluated and shown in Fig. 2.

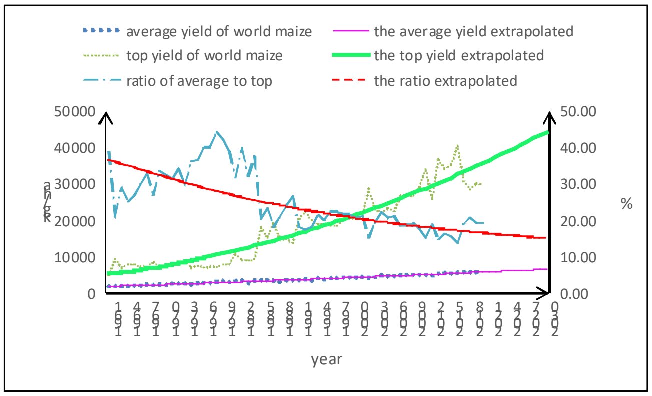

Fig. 2: Average and top yields of world maize in 1961 to 2020 and to 2030

As shown in Fig. 2, the ratio of extrapolated average to top yields of world maize between 2021 and 2030 is 16.39% in 2021, 16.24% in 2022, 16.09% in 2023, 15.95% in 2024, 15.81% in 2025, 15.67% in 2026, 15.53% in 2027, 15.40% in 2028, 15.27% in 2029, and 15.14% in 2030, respectively. In other words, average yield of world maize is projected to be decreasingly approaching 15% of the top by 2030, or the gap between these two kinds of yield will be widening in ensuing decade. Top (national) yield of world maize is considered potential limit of the average because the latter will 'chase after' but never approach the former. The variation trend of ratio between average and top yields of world maize over time may be temporarily downward but will be eventually upward as the average increasingly approaches the top later on.

Effects of global warming on world maize yields based on unary regression model

It is worldwide acknowledged that annual global mean temperature has been rising in slight fluctuation over time since industrial evolutionary. As above-analyzed, both average and top yields of world maize rise in 1961 to 2020 and to 2030 in general. Theoretically, there must exist certain inner correlations between annual global mean temperature and the yields of world maize because temperature is an essential factor for the crop to grow and yield. Though all climatic factors such as sunlight, temperature, precipitation and gases each has respective contribution to the growth and yield of world maize, but only the variation (rise) of annual global mean temperature is observed and proved to be the result of higher CO_2 concentration in atmosphere. Theoretically speaking, world maize yield is dependent mainly on climatic factors at global or macroscopic level while mainly on nutritional condition on local or microscopic scale. At global or macroscopic level in climate change, sunlight and gases though have somehow changed and have contributed to the yields of world maize inclusively in the effect of global warming, for they cause the decrease or increase of global mean temperature directly or indirectly. And the variation of annual precipitation over time on global scale does not show any trend of increase or decrease. Therefore, theoretically for the sake of simplification, the contribution of sunlight, precipitation and gases yearly on global scale can be treated as constant in modelling, to the yields of maize worldwide planted in different seasons.

Thus, taking global mean temperature as independent (X) while world maize yield as dependent (Y), the impacts of global warming on average and top yields of the crop from 1961 to 2020 are respectively regression-modeled with constant and shown as in formula (6) and (7).

$$Y = -1706.926 - 1293.786 + 117.440X^2 \tag{6}$$

In formula (6), R squared = 0.819 while F = 128.547 at great significant level.

As shown in formula (6), global warming exerts positive effect on average yield of world maize from 1961 to 2020 with the quadratic function better simulated having one of two highest R squared values than 0.818 of linear, 0.817 of logarithmic, 0.815 of inverse, 0.761 of compound, 0.762 of power, 0.763 of S, 0.761 of growth, 0.761 of exponential and 0.761 of logistic, and sharing both R squared and F value of the cubic with same equation (viz. coefficient b3 = 0.000).

$$Y = 144166.548 - 33887.721X + 1749.277X^2 \tag{7}$$

In formula (7), R squared = 0.776 while F = 98.628 at great significant level.

As shown in formula (7), global warming exerts positive effect on top yield of world maize from 1961 to 2020 with the quadratic function better simulated having one of two highest R squared values than linear with 0.773, logarithmic with 0.772, inverse with 0.769, compound with 0.751, power with 0.752, S with 0.753, growth with 0.751, exponential with 0.751 and logistic with 0.751, and higher F value than 98.523 of the cubic with same R squared. According to different values of b2 coefficients in above quadratic functions, average yield of world maize from 1961 to 2020 was positively affected by global warming less than the top, which partly drives the gap between these two yields widened gradually in the past.

Theoretically, the long-term variation of any crop yield over time shows some trend of S-shaped curve, where it is positively accelerated before the middle turn-point while negatively after that towards final limitation. For the crop whose current average yield is in low place before the turn-point of such S-shaped curve (e.g. below 1/3 of potential limit), the opportunities for improving global production should be mainly dependent on raising the crop yield in high-yield countries with high efficiency.

CONCLUSION

Our study concludes that: between 2021 and 2030, average yield of world maize is projected to be 5989 kg·ha-1 to 6703 kg·ha-1 while the top yield from 36530 kg·ha-1 to 44271 kg·ha-1, or the average ranging from 16.39% decreasingly to 15.14% of the top; from 1961 to 2020 global warming exerts positive effect on average yield of world maize less than on the top, which partly drives the gap between these two yields widened obviously; for world maize by 2030, the opportunities for improving global production should be mainly dependent on the advantage of high-yield countries.

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