|  |  |  |  |
| --- | --- | --- | --- |
|  | city | county | Field |
| 1 | d:\Documents\Tencent Files\2453212698\FileRecv\MobileFile\Image\M7`B~V)TC06)`%T~D%PW$W0.png | d:\Documents\Tencent Files\2453212698\FileRecv\MobileFile\Image\){3K$UR54FJ4FH{MJ6MD@~W.png | d:\Documents\Tencent Files\2453212698\FileRecv\MobileFile\Image\Y5TAR6KBRG5OXCB9ANJY2LK.png |
| 2 |  |  |  |
| 3 |  |  |  |

Nonlinear temperature effects indicate severe damages to US crop yields under climate change

**Materials and methods**

**Sample sites （climate data, soil, winter wheat summer maize on field date, and study sites）**

Three groups high-quality weather stations were selected for this study. Each group consists of three sites, which correspond to meteorological conditions in large city, small town, and farmland. Meteorological data for large cities and small towns was from National Meteorological Network of the China Meteorological Administration (CMA). Cropping environment meteorological data was applied with Chinese Ecosystem Research Network (CERN). Daily maximum and minimum temperature and precipitation are available for each weather station, and solar radiation can be converted from observed sunshine hours (Black et al. 1954; Jones1992).

The soil data in our study included soil bulk density (BD), saturated volumetric water content (SAT), drained upper limit (DUL), and 15-bar lower limit (LL15) for different soil layers.

Details of these data for the study area are given in table 1. Clay (partial diameter < 0.002) content (%), Silt (>0.002 and 0.05 mm) content (%).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Terms | Sites group A | | | | | Sites group B | | | Sites group C | | | |
|  | Yucheng\_cropland | yucheng | | DeiZhou | | Fengqiu\_cropland, small city, big city | | | luancheng | | | |
| Latitude | 36°40’ | |  | |  | 35°00' | 35.25 |  | | 37°53' | 37.52 |  | |
| Longitude | 116°22’ | |  | |  | 114°24' | 114.02 |  | | 114°41’ | 114.38 |  | |
| elevation | 21m | |  | |  | 67.5m | 69 |  | | 50.1m | 52.9 |  | |
| radiation | 5225MJ/year/m2 | |  | |  | 4731 MJ/year/m2 |  |  | |  |  |  | |
| rain | 582mm | |  | |  | 605mm |  |  | | 530mm |  |  | |

At all the sites, the cropping system was a winter wheat and summer maize double cropping rotation. These sites represent typical agricultural areas in the North China Plain. The North China Plain is characterized by temperate humid/semi-humid climate where summer maize is sown in mid-June and harvested in late September in a winter wheat and summer maize double cropping system (two crops a year). And the three sites, in each site group, represent significant different main part scale of cities. The study period was from 2005 to 2014 year in site group B and C. the site group A was studied from 1980 to 2017 year.

Crop data including varieties, major phenological stages, yields and management practices were recorded by setting the field experiments for Luancheng station, Yucheng, and Fengqiu stations. Winter wheat Variety KN199, A and B were planted at the LuanCheng, YuCheng and FengQiu sites respectively.

Long-term records (1981–2010) of key phenological stages, biomass

Observed phenological stages include time of sowing, emergence, ﬂowering and maturity. The cultivation and chemical fertilizer management were following the local practices. Monitoring on sowing and harvesting date, phenological development, plant density, above ground biomass and grain yield were carried out using the standard methods. At harvesting, plants were harvested manually and threshed to get the grains. After air-dried to a constant weight (13% water contents), grain weight from each plots were recorded to calculate the grain yield per hectare.

**Modelling of temperature impact in APSIM, WOFOST, and DSSAT**

**2.2 APSIM model and its parameterization**

The Agricultural Production Systems sIMulator (APSIM) is internationally recognized as a highly advanced simulator of agricultural systems (Holzworth et al., 2014; Keating et al., 2003; Wang et al., 2002). Version 7.9 was used to simulate above-ground biomass, grain yield, water and nitrogen use of wheat and maize crop at the study site. The phenological development of crop from emergence towards maturity is driven by the accumulation of thermal time, with the rate of accumulation modified by vernalization and photoperiod for wheat and photoperiod for maize before floral initiation. The growth of aboveground biomass was simulated using stage-dependent radiation use efficiency (RUE) together with the intercepted radiation. RUE is further modified by suboptimal temperatures and stresses of water and nitrogen if the water and/or nitrogen supply is not sufficient to meet the crop demand. A detailed description of APSIM can be found on <http://www.apsim.info>.

APSIM contains numbers of modules (Keating et al., 2003). The key modules used in this study were Wheat and Maize (crop growth and development), Management (setting crop management procedures), Water (soil hydraulic parameters), Soil Organic Matter, Soil Water (soil water balance), Initial Water (initial soil water status), Initial Nitrogen, Climate control and Weather data on daily step for the period of the simulation (including daily maximum and minimum temperature, rainfall and solar radiation). Potential crop water uptake was simulated by relationships with root exploration and extraction potential (Keating et al., 2003). Where water was a limiting factor, above-ground biomass accumulation was the product of available soil water and conversion efficency in transpiration, which was modiﬁed by vapour pressure deﬁcit. Where water was a non-limiting factor, biomass accumulation was the product of intercepted radiation and radiation use efficency (Bassu et al. 2011). CO2 concentration controlled by Climate control module affects radiation use efficiency and transpiration efficiency. Temperature and nitrogen deﬁcits were also considered in simulating the potential growth (Asseng et al., 2011). During the simulation, P and K were not considered and they were automatically set at adequate level.

The soil water balance was simulated using a cascading water balance model (SoilWat). The plant-available water capacity (PAWC) of each soil layer was speciﬁed by a crop lower limit and a drained upper limit. In this study, the lower limit and upper limit for each soil layer were estimated based on the soil water contents at wilting point and field capacity.

The Manager Input was parameterized with the real sowing, management practices and the characters of the cultivars used. The planting density of maize was set up at 8 plants/m2 and winter wheat at 300 plants/ m2, for all the simulation scenarios. Sowing date was on 15th October for winter wheat, 15th June for summer maize and 10th May for spring maize. Irrigation amount was set at 75 mm/application for all irrigations. For FI strategy simulation, irrigation was automatically added whenever the soil water contents for the top 1 m soil layer was below 65% of field capacity. Nitrogen application was set at 180 kg/ha for winter wheat and 220 kg/ha for maize split half as base fertilizer and half at jointing stage for wheat and at 9th leaf stage for maize.

APSIM has been extensively validated for wheat and maize in NCP. Many published papers have shown that parameters of crop growth could be predicted by APSIM model, including above ground biomass accumulation, final grain yield, crop water use of wheat and maize in response to water supply in the NCP. Initially, the calibration of the APSIM was based on the parameters of Sun et al. (2015) and was further adjusted based on the experimental results from 2007-2016. The parameter calibration process is as the following: Step1, input APSIM parameters from previous research of Sun et al. (2015). Step 2, the cultivar parameters were trimmed using a trial and error method to match the simulated crop anthesis and maturity dates to the observed data from 2007 to 2011. Step 3, the model was run with the trimmed crop parameters, and the performance was evaluated according to the biomass, grain yield, and ET for wheat and maize from 2007 to 2011. After calibration, the model was further validated using the experimental data from 2011-2016. For all the simulations, irrigation and fertilizer were applied according to the actual practices.

Model performance was evaluated using the slope and the coefficient of determination (R2) of the regression lines between simulated and observed values. The root mean square error (RMSE) was used to quantify the deviation of the modeling results from the observed data as:

(1)

where *Si* is the simulation value, *Oi* is the observation value, *n* is the number of the simulation or observation values.

**2.2.3. Data extracted from literature review**

**瓦赫宁根的作物模型的生育期参数是通过调发育期速率，而APSIM和Dssat模型均是调整作物所需要的积温决定生育期，这两种模式那种更能抓住温和升温对作物的影响。**