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Attributing Regional Trends of Evapotranspiration and Gross Primary Productivity with Remote Sensing: A case study in the North China Plain

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Abstract

Attributing changes of evapotranspiration (ET) and gross primary productivity (GPP) are crucial for impacts and adaptation assessment of the agro-ecosystems to climate change. Simulations with VIP model revealed that annual ET and GPP were slightly increasing from 1981 to 2013 over the North China Plain. The tendencies of both ET and GPP were upward in spring season, while the trends are weak and downward in summer season. A complete factor - separation analysis illustrated that the relative contributions of climatic change, CO_2 fertilization and management to ET (GPP) trend were 56 (-32)%, -28 (25)% and 68 (108)%, respectively. The decline of global radiation resulted from deteriorated aerosol and air pollution was the principal causes of GPP decline in summer, while air warming intensified the water cycle and advanced the plant productivity in the spring season. Agronomical improvements were the principal drivers of crop productivity enhancement.

Key words: Climate change; Contribution; VIP model; Evapotranspiration; Gross primary productivity

1. Introduction

Terrestrial hydrological and carbon cycles are intimately coupled via transpiration and photosynthesis processes which are regulated by plant leaf stomata. Due to land use/cover changes, intensified agricultural management and climatic change, terrestrial eco-hydrological processes have been noticeably shifted at multiple spatiotemporal scales (Tian et al., 2011; Douville et al., 2013), for example, prevailing irrigation and application of chemical fertilizers have raised soil moisture, evapotranspiration (ET) and crop productivity, etc. In some regions the effects of human activities are the same magnitude as, or even exceed the impacts of global warming on the productions of agro-ecosystems (Haddeland et al., 2014). In the last decades, global consumptive water use and carbon fixation by terrestrial ecosystems are demonstrated to be slightly increasing with more efficient water use, corresponding to changes of climatic factors and fertilization effect of elevated atmospheric CO_2 concentration (Yan et al., 2013; Nayak et al., 2013). Spatiotemporal patterns of water and carbon fluxes at regional scale are changing under global change (Zeng et al., 2014;Liu et al., 2012).

As ET being the major component of water budget in the water limited basins, its long term tendency has been taken as an indicator for diagnosing the intensification of regional water cycle. The complementary relationship between actual and potential ET may reveal some clues of hydrological changes. Observations in the last decades illustrated that potential evaporation rates (ET_p)(represented as pan evaporation) were decreasing in Europe, U.S., China, India, Australia (Brutsaert, 2006; Katul et al., 2012), implicating the decline of available energy and aerodynamics devoted to latent heat flux over the land surface. The climatic factors dominating ET_p change are usually diverse. For example, over the North China Plain (NCP) the changes of ET_p were mainly attributed to declines of global radiation and near surface wind speed (Tang et al., 2011; Song et al., 2010). However, in southern Turkey a noticeable decline of ET_p was attributed to enhanced air humidity associated with the expansion of irrigation acreage and more water evaporated into the atmospheric boundary layer (Ozdogan and Salvucci, 2004). Burn and Hesch (2007) revealed that decreasing wind speed and raised water vapor deficit were responding to trend of ET_p in Canadian Prairies. At large scale, precipitation is usually the principal factor determining actual ET changing, such as Qian et al. (2007) presented that increase of ET in the Mississippi River basin was following precipitation propensity, while the effects of solar radiation and air temperature changes were minor.

Terrestrial eco-hydrological processes are driven by climate and modulated by human activities. Generally climate warming enhances atmospheric evaporative demand, while CO_2 fertilization stimulates photosynthesis and inhibits leaf stomatal conductance, leading to more biomass accumulation and higher water productivity (Field et al., 1995; Buckley and Mott, 2013). Simultaneously, land use change and land management also noticeablly affect the ecosystem production and hydrological fluxes (Shi et al., 2011). Separating the contributions of climatic change, CO_2 enrichment and human activities to the long term trends of water and carbon cycles is critical for assessment of ecosystem responses and resilience to environmental changes. Some researchers have explored the relative contributions of climate change and vegetation dynamics to changes of global land surface evapotranspiration and river runoff (Betts et al., 2007; Piao et al., 2007; Alkama et al., 2010; Liu et al., 2012; Chen et al., 2014; Banger et al., 2015), but the conclusions are inconsistent yet. Climate change dominated the inter-annual variability of ET, while land use changes and agricultural practices and techniques exerted more discernable effects on water cycle in long term (Liu et al., 2012). However, Alkama et al. (2010) and Shi et al. (2011) demonstrated that climate change is the predominant driver of the changes of global ET in 20th century. For the contributions of climate change to vegetation productivities at large scale may be explored by ecosystem models or statistical models. Piao et al. (2015) documented that elevated atmospheric CO_2 and nitrogen deposition were the critical contributors to terrestrial greening over China in the last three decades; Baker et al. (2010) figured out that climate anomalies in springtime were the most frequent drivers to annual GPP variability in the North America; Nayak et al. (2013) reported that climate change had a relatively small but significant control (15%) on the trend of terrestrial net primary production (NPP) over India during 1981to 2005. In the crop ecosystems, contributions of climate change, cultivar renewal and agronomic management to change of crop yield have been separated with crop or statistical models (Yu et al, 2012; Song et al.,2014; Bai et al., 2015; Guo et al., 2014; Wang Z. et al., 2016). The impacts of climate change on crop yield may be positive or negative in different regions, depending on the tendencies of the dominant factors (Ewert et al., 2015).

As one of the granaries in China, North China Plain (NCP) is experiencing challlenges of agriculture sustainability due to global change and social development. Thereby, it is crucial to understand the impacts of climate change on the productions of cropping systems. Over the plain, winter wheat – summer maize double cropping system is prevailing, supported by irrigation, fertilizer and agronomical techniques. *In situ* measurements, agricultural annals and regional remotely sensed vegetation index dataset all illustrated that both wheat and maize productivities have enhanced remarkably during the last three decades (Yuan and Shen, 2013); correspondingly, the seasonal water consumption and water use efficiency are also slightly improved (Zhang et al., 2011). The achievement of long term increasing grainproduction is related to the active adoption of new varieties for stabilizing, extending the length of crop growth period, as well as agronomical technique advancement (Liu et al., 2010; Sacks and Kucharik, 2011). Currently, water amount for food production is consisted of 65% of total water consumption here. Further, along with the gradually augmented domestic and industrial water requirement, groundwater in some parts of the plain has been over-exploited, and the environmental water requirement is generally under deficit conditions (e.g., MWR, 2010). Facing with the rapid deteriorating agricultural environment, some critical issues are still unclear, such as, what mechanisms drive the evolutions of eco-hydrological processes over this plain? What are the impacts of climate change on the cropping systems?

In this study, the VIP eco-hydrological dynamic model integrated with NOAA-AVHRR remotely sensed normalized difference of vegetation index (NDVI) is employed to assess the spatiotemporal evolutions of ET and vegetation GPP over the NCP during 1981 to 2013. By numerical experiments with the VIP model and the factor separation method, the contributions of climate change, fertilization of atmospheric CO_2 enrichment and agronomical practices and technological advancement to crop water consumption and productivity are then analyzed, and the relevant mechanisms are discussed.

2. Method and materials

2.1 Study site

The NCP is one of the country's granaries, extending from latitude 32°00′ to 40°24′N and longitude 112°48′ to 122°45′E (Fig. 1(a, b)). It is located in the eastern part of China with

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an area of 33×10^4 km^2, which is an alluvial plain developed by the intermittent flooding of the Huang, Huai and Hai Rivers and 72% is cultivated as farmland. The warm temperate climate varies gradually from sub-humid in the southern to semi - arid in the northern parts. The annual precipitation ranges from 500 - 1000 mm, occurring irregularly among seasons and more than 70% falls in summer. Soil moisture deficit happens widely during the the spring and early summer period. Besides soybean/millet/sorghum/cotton, the double cropping system of winter wheat - summer maize is prevailing in the plain, where wheat and maize are the most common harvest crops in summer and autumn seasons, respectively. Due to insufficient precipitation, the spring crops (such as wheat) usually need supplemental irrigation to form favorable production.

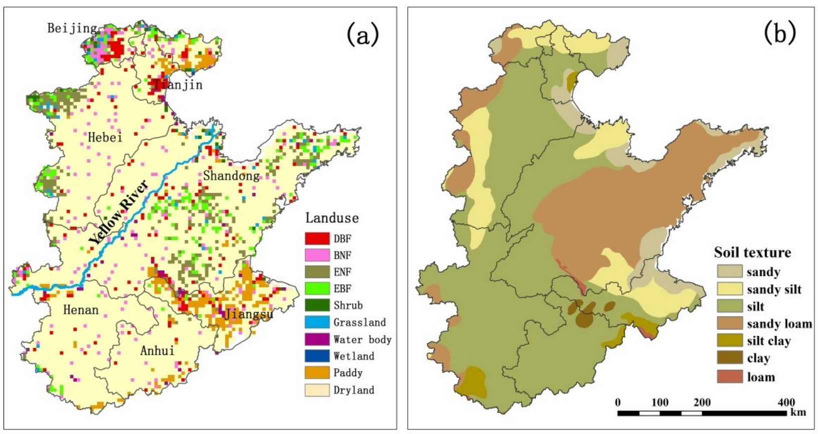

Fig. 1 Land use/cover (a) and soil texture (b) of the North China Plain (NCP) (DBF: Deciduous Broadleaf Forest; BNF: Broadleaf and Needle leaf Mixed Forest; ENF: Evergreen Needle leaf Forest; Evergreen Broadleaf Forest)

2.2 The VIP eco-hydrological Model

The physically process-based VIP (Vegetation Interface Processes) eco-hydrological model is designed to simulate the exchanges of energy, water and carbon between terrestrial ecosystem and atmosphere (Mo et al., 2014). In the model, ET is termed as the summation of canopy transpiration, evaporation from canopy intercept and soil surface, computed separately with the Penman-Monteith Equation. Transpiration and photosynthesis processes are coupled through the Ball-Berry relationship between leaf stomatal conductance and net assimilation rate. On carbon cycle aspect, leaf carbon fixations on sunlit and shaded leaves groups are predicted with the biochemical schemes for C3 (Farquhar et al., 1980) and C4 plants (Collatz et al., 1992). In the radiation budget scheme, shortwave radiation transfer in canopy distinguishes the leaf spectral properties of visible and near infrared radiation, as well as fraction of direct beam and diffusive irradiance in global radiation. Precipitation throughfall - runoff generation over the land surface is calculated with a curve - number (CN) type equation at daily scale, using the daily net precipitation and the moisture deficit of upper-soil layer in this study. Simulation of soil water movement in root zone is carried out with a discrete Richards Equation in three layers. The crop and natural vegetation growth modules are also embedded in the model to simulate the biomass mass accumulation and carbon cycle.

2.3 Data

The VIP model input data include land use/cover, soil physical properties, and atmospheric forcing variables. GIMMS AVHRR 15-day normalized difference of vegetation index time series (NDVI3g) from 1981 to 2013 is used to retrieve the vegetation leaf area index and other land surface characteristics (https://nex.nasa.gov/nex/projects/1349/wiki/general_data_description_and_access/) (Pinzon and Tucker, 2014). The land use classification is originated from both Landsat TM images (www.geodata.ac.cn) and MODIS remote sensing products, in which the farmland is classified as rice paddy and dryland. Soil textural data are at a scale of 1:1,000,000 represented as fractions of sand, silt and clay, by which the parameters of soil porosity (θ_{sat}) and saturated hydraulic conductivity (K_{ws}, mm s^{-1}) are estimated as Bonan (1996). Daily climate variables (air temperature, water vapor pressure, wind speed, sunshine duration and precipitation) recorded at 87 climatic stations (http://cdc.cma.gov.cn/) in and around the study area are available for generating the spatial atmospheric forces. The NDVI data are error-checked and the erroneous data are replaced by interpolation with the preceding and subsequent values according to the time series by the Savitzky–Golay (SG) filter (Savitzky and Golay, 1964), and then the daily values are derived with the Lagrange polynomial. Vegetation leaf area index (LAI) is retrieved from NDVI with empirical relationships for different plant function types.

The data used for model validation are field flux measurements with eddy covariance technique at Yucheng (116°38′E, 36°57′N), Daxing (116°25′E, 39°37′N), Miyun (117°19′E, 40°38′N) and Guantao (115°8′E, 36°31′N) sites over the plain. The cropping systems at the Yucheng, Daxing and Guantao sites are all rotations of winter wheat – summer maize, while land cover is dwarf shrub at the Miyun site. The eddy covariance data are processed with general procedures (Liu and Xu, 2013). GPP data are available only at Yucheng site. In addition to the eddy fluxes, grain yield records of wheat and maize in county statistics are also used to verify the GPP predictions at regional scale.

2.4 Model implementation and experimental design

2.4.1 Simulation setup

The model simulations were conducted at 8 - km spatial resolution and half - hour time step. The cropland is classified into wheat and maize or rice double cropping systems. Atmospheric driving forces are interpolated from daily meteorological variables recorded at the climatic stations to grid cells with a gradient inverse distance square method (GIDS), which accounts for the effects of elevation, latitude and longitude (Nalder and Wein, 1998). Estimated with sunshine duration in a linear relationship, the global radiation is subdivided into direct visible and near infrared parts, as well as direct beam and diffusive components with Weiss and Norman (1985). The daily air temperature is extended to hourly values with a sinusoid function based on the daily maximum and minimum temperatures (Cambell and Norman, 1998). During the winther wheat growing period, irrigation water is supplied when water storage in the root zone is below 60% of the field capacity. Summer maize is set to be irrigated not more than one time in its growth period. The simulation is conducted with prescribed daily LAI series retrieved from remotely sensed NDVI series for eco-hydrological prediction from 1980 to 2013, in which the first year is taken as warming up.

2.4.2 Separation of the contributions of climate change and management effects

By using a general function, *f*, the scalar fluxes (water vapor and carbon) between land surface and the atmosphere are determined by climate factors (M), atmospheric CO_2 fertilization (C) and agronomical management and technological advancement (In this study we assume the long term trend of leaf area index (LAI) may represent the effects of human activies on ecosystems of crop and natural ecosystems. Human activities to the agro-ecosystem include renewals of cultivars, irrigation facility improvement, fertilizer use application, soil quality amelioration, etc.), namely,

$$f = F(M, C, LAI, \dots) \tag{1}$$

The changes of f contributed by a single factor (expressed as f_i) and its interaction with another factor (expressed as f_{ij}) can be decomposed by the Taylor expansion as,

$$f_i = \frac{\partial F}{\partial x_i}\Delta x_i + \frac{1}{2!}\frac{\partial^2 F}{\partial x_i^2}\Delta x_i^2 + \cdots + \frac{1}{n!}\frac{\partial^n F}{\partial x_i^n}\Delta x_i^n \tag{2}$$

$$f_{ij} = f_i + f_j + \frac{\partial^2 F}{\partial x_i \partial x_j}\Delta x_i \Delta x_j + \cdots \tag{3}$$

where x_i and x_j ($i \neq j$) represent M, C and LAI, respectively. The factor separation methodology from Stein and Alpert (1993) and Alkama et al. (2010) is used to category the contributions of climate change, CO_2 fertilization and LAI, and their interactions to long term trends of ET and GPP. Similar to Alkama et al. (2010), the total effect, f_{123}, is expressed as,

$$f_{123} = f_1 + f_2 + f_3 + f^{12} + f^{13} + f^{23} + f^{123} \tag{4}$$

With

$$f^{12} = f_{12} - f_1 - f_2 \tag{5}$$

$$f^{13} = f_{13} - f_1 - f_3 \tag{6}$$

$$f^{23} = f_{23} - f_2 - f_3 \tag{7}$$

Where f_1, f_2 and f_3 are the direct contributions of climate change, atmospheric CO_2 enrichment fertilization and agronomical management, respectively; f^{12} is the contribution of interactions of climate change and CO_2 enrichment; f^{13} is the contribution of interactions between climate change and management; f^{23} is the contribution of interactions between CO_2 fertilization and agronomical management; f^{123} is the contribution of interactions between climate change, CO_2 fertilization and agronomical management.

Seven numerical experiments designed to fully distinguish the contributions of climate change, CO_2 fertilization and agronomical management are conducted by the VIP model over the NCP from 1981 to 2013. The experiments are as following:

(1) f_{123} (“all factors”): Current climate, CO_2 and LAI spatiotemporal pattern;

(2) f_1 (“climate change effect”): Current climate, but atmospheric CO_2 concentration is fixed at year 1981, and LAI pattern is set as the multi-year average;

(3) f_2 (“CO_2 fertilization effects”): Climate and LAI fixed at a specific year, but current CO_2 concentration;

(4) f_3 (“management effect”): Climate and CO_2 concentration are fixed a specific year, but current LAI pattern is used;

(5) f_{12} (“climate change and CO_2 fertilization effects”): LAI pattern is fixed, but current climate and CO_2 concentration are used;

(6) f_{13} (“climate change and management effects”): CO_2 concentration is fixed, but current climate and LAI pattern are used;

(7) f_{23} (“CO_2 fertilization and management effects”): Climate is fixed at 1981, but current CO_2 and LAI are used.

The trends of annual ET and GPP in the above experiments are calculated. According to Eq.(4) to Eq.(7), the contributions of climate change, CO_2 fertilization and management to ET and GPP long term trends are separated.

3. Result analysis

3.1 Model Verification

3.1.1 Validated with eddy covariance measurements

The VIP model is used to simulate the hydrological, energy partitioning and crop growth processes at the four sites of eddy flux measurement. Here, eddy covariance measurements of daily ET and GPP are employed to verify the model predictions (ET is available in all the sites, but GPP is only available at one site). The land surface characteristics are relatively homogeneous surround the measuring sites, ensuring the footprint for measured fluxes. The meteorological information measured at each site is used to drive the VIP model. It is shown that the agreements are quite satisfactory for both ET and GPP (Fig.2 and Fig.3). Totally, there are 9-year daily ET data and 3-year daily GPP data for comparison with the model simulations. The coefficients of determination (R^2) are above 0.76 for all the sites. At annual scale, the absolute relative biases of predicted ET are ranged from 1.5 to 12.6% in the 9-year dataset, and biases of GPP are from 2.0 to 8.8% in 3-year data. Therefore, the model performance is quite well and reliable for vegetation/crop productivity and water consumption predictions. The biases may be stemmed from both meausrements and model uncertainty. Mo et al. (2012) showed that the canopy leaf area index (LAI) and photosynthetic capacity (carboxylation rate for C3 crops and photon quantum use efficiency for C4 crops) were the most sensitive parameters to the model efficiency. Here, taking Yucheng site as an example, annual ET and GPP may increase 1.6% (2.6%) and 3.0% (15.9%) respectively as LAI (photosynthesis capacity) is increased by 20%.

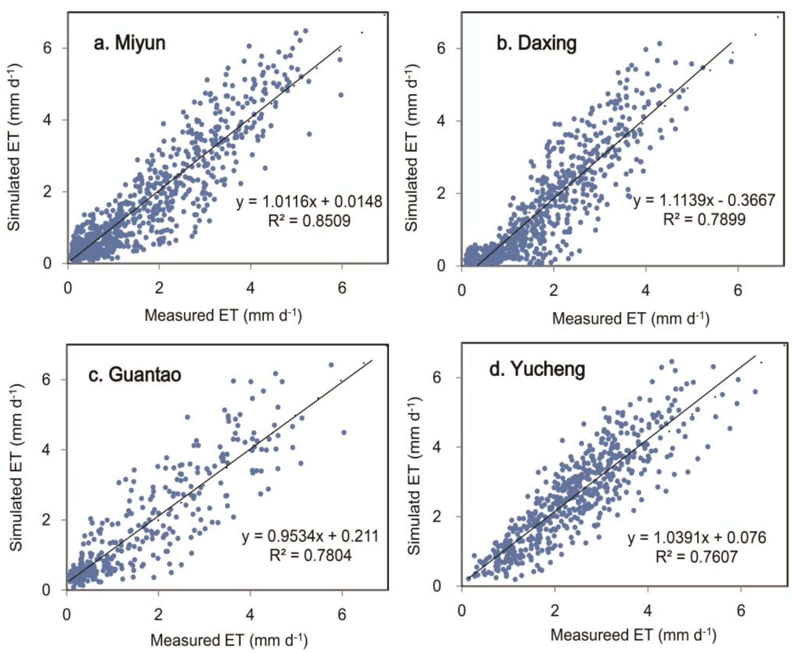

Fig.2 Comparison of the simulated daily ET and GPP with the eddy covariance measurements

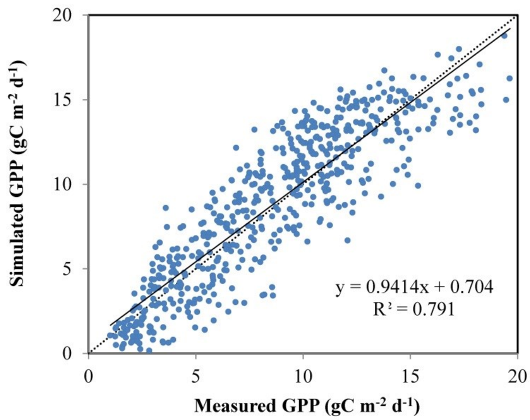

Fig.3 Comparison of the simulated GPP with eddy covariance measurements at the Yucheng site

3.1.2 Validated with the statistical yield records

The simulated GPP is also validated with the statistic staple crop grain yields at county level. The yield per hectare is converted to equivalent GPP per square meter. As shown in Fig.4 (years of 2000 and 2005 are used), the agreement is satisfactory with the coefficient of determination (R^2) of 0.43 and 0.51 (p<0.001), respectively. There are remarkable spatial variations of crop yields resulted from diverse conditions of climate, soil and management. In the simulation, it is found that the spatiotemporal evolution of greenness is the dominant factor of yield patterns. Greenness represented by the vegetation index is an appropriate indicator of crop productivity under environmental stresses (Hu et al., 2014). In the areas with high vegetation index and favorable irrigation facilities, the yield losses may be caused by heat waves or pest infections in the maturity stage.

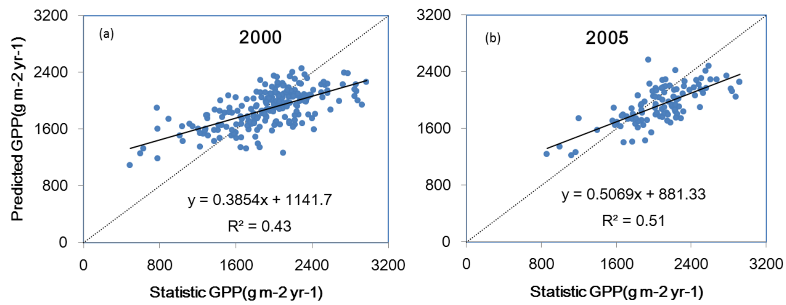

Fig.4 Comparison of the predicted GPP and statistic yield derived GPP at county scale in 2000 and 2005.

3.2 Trends of climate, crop productivity and ET

Changes of climate variables and agro-ecosystem management are the dominant driving forces for evolution of regional eco-hydrological processes. Intra-seasonal variations of climatic variables may exert different impacts on the crop water consumption and carbon assimilation. In the last three decades, air temperature is rising, but sunshine duration and wind speed are decreasing significantly over the plain, associated with global climate change, aerosol and air pollutions. Soil amelioration, genetic improvement, irrigation facility constructions and application of chemical synthesis fertilizer are considered to be the principal factors that have propelled productictiy close to the attainable level(Yu et al., 2012; Lobell and Burke, 2010).

3.2.1 Changes of climatic variables

Grid averages of the climatic variables were interpolated with GIDS (Gradient Inverse Distance Square) method over the North China Plain from 1980 to 2013. Nevertheless inhomogeneous distributions of the climatic variables, the spatially averaged trends were clear (Table 1). At annual scale, global radiation, air temperature (especially minimum temperature) and wind speed were significantly changing (p<0.01). At monthly scale, radiation was declining in all the months except March, but only trends in June to September were significant (p<0.01); Significant increasing of air temperature is occurred in spring (February and March) and early summer (May to July); Wind speed was decreasing

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significantly (p<0.01) in all the months except August. However, no significant trends were detected for both precipitation and water vapor pressure throughout each month. As a consequence, water vapor pressure deficit was exaggerated along with the rising of air temperature, which was expected to intensify the atmospheric water vapor demand and offset the negative effects of declining radiation and wind speed on potential evaporation). These changes in climatic variables have exerted remarkable impacts on the crop phenological stages, water consumption and productivity during the last three decades over the North China Plain (Liu et al., 2010).

Table 1. Inter-annual trends of monthly sunshine duration, precipitation, air temperature, relative humidity and wind speed (Significant levels: * for p<0.05; **for p< 0.01).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Sun(h/yr)	-0.026	-0.036*	0.015	-0.012	-0.015	-0.039**	-0.040**	-0.052**	-0.060**	-0.018	-0.017	-0.020
P(mm/yr)	-0.129	0.212	-0.279	0.354	0.049	-0.472	0.608	0.456	0.694	-0.706	0.223	0.084
T(°C/yr)	0.022	0.058*	0.078**	0.030	0.042**	0.029*	0.030*	0.017	0.020	0.044*	0.025	0.018
rh(%/yr)	-0.065	0.115	-0.260*	-0.079	-0.139	-0.074	-0.080	-0.074	0.057	-0.125	-0.094	-0.091
U(m/s/yr)	-0.016**	-0.012**	-0.012**	-0.020**	-0.021**	-0.019**	-0.015**	-0.006	-0.014**	-0.017**	-0.015**	-0.012**

3.2.2 Changes of Greenness and GPP

Here remotely sensed NDVI is expressed as vegetation greenness. Averaged over the growth period (from March to October), vegetation greenness was significantly increasing from 1980s with a trend of 0.64/yr (p<0.001) and coefficient of variation (CV) of 2.4% (Fig.5(a, b)). It was noted that the maximum inter-annual variation of greenness was 5.4% between two consecutive dry and wet years (1989 and 1990) with 280 mm difference of annual precipitation. The distinguish differences of greenness occurred in June to December. At annual scale greenness was weakly related with precipitation; however, in growing season, greenness was noticeably correlated with monthly precipitation in April, May, June, September and November (r =0.29 ~ 0.53, p<0.1). The reason is that the monthly rainfall is

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generally lower than the atmospheric evaporative demand in spring season, and the water deficit to transpiration generally stresses the plant growth. Unlike precipitation, greenness anomalies are positively correlated with the detrended air temperature (r^2=0.16, p<0.05), implicating that recent climate warming has stimulated vegetation growth through extending the growing stage and through pushing photosynthesis in water no-limited regionss (Mao et al., 2012; Nemani et al., 2003).

Regional greenness trends showed remarkably diverse (Fig.6(a, b)). Except climate change, human activities also exerted critical impacts on the land greenness variations. In the low plain of Hebei province, saline - alkali land amelioration and irrigation facilities improvement have contributed greatly to the greenness enhancement in the 1980s to 1990s. In addition, atmospheric nitrogen deposition was also regarded as a positive driver for the land greening, since the nitrogen deposition has averagely increased by 25% from 1990s to 2000s in North China (Jia et al., 2014; Piao et al., 2015). Spatially, greenness over 91.3% of the NCP was increasing, in which the most distinctive grids distributed in the southern parts and the belt along the yellow river channel, where water supply was usually sufficient. In the northern part, tendencies of greenness in a number of grids were decreasing significantly at p=0.1 level, which were resulted from less irrigation supply to farmland in springtime and rapid expansion of built-up occupations around cities and towns, such as Beijing and Tianjin metropolitans.

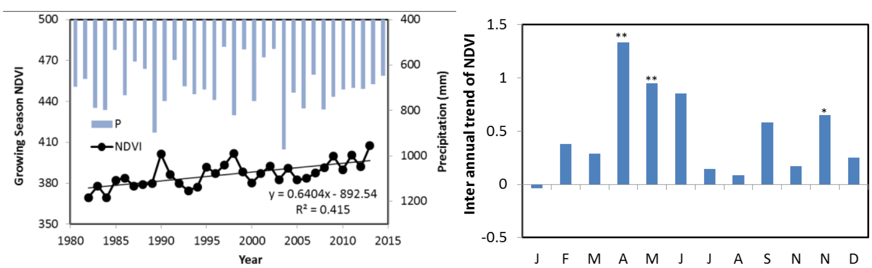

Fig.5 Spatial average trends of growing season NDVI at annual (a) and monthly scales (b) (Significant levels: * is p<0.05; **is p< 0.01).

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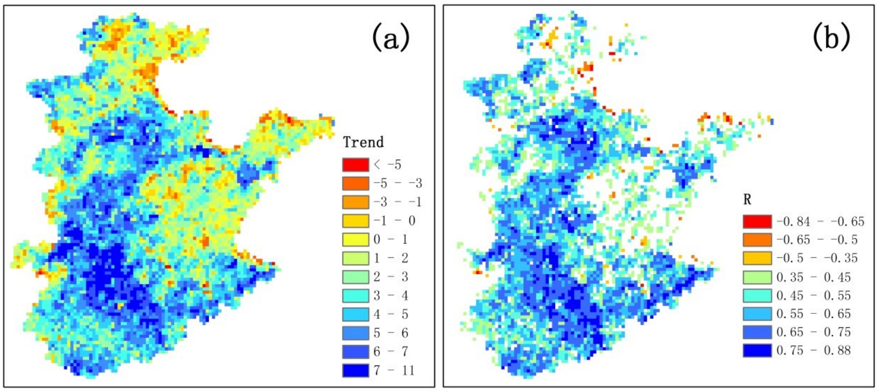

Fig.6 (a) Spatial distributions of NDVI trend in growing season and (b) the Pearson coefficients of NDVI trend above p<0.05 significant level

The spatially averaged GPP was 1913±584 gC $m^{-2}yr^{-1}$ with CV of 6.8% predicted by the VIP model from 1981 to 2013, showing great spatial variability (Fig.7). Low crop productivity was resulted from fields with saline-alkali soil in the low lands nearby the coast of Bohai Sea, where almost no favorable water was available for irrigation purpose in springtime. Averagely, the increasing trend of GPP was significant with a slope of 8.2 gC m^{-2} yr^{-2} (r=0.60, p<0.01). It was noticed that the average annual GPP was increasing steadily from 1980s to 2000s, compounded by decadal variations of the climate and elevated atmospheric CO_2, as well as the improvement of agricultural practices and techniques. Trends of annual GPP were positive over 87.9% of the study region. As shown in Fig.7, the obvious increasing trends were located in the mid and southern areas, while most of the decreasing trends occurred in the eastern and northern parts, where water for irrigation was considerably reduced in spring season because of competing demand of the domestic and industrial water uses.

At monthly scale, GPP was increasing in all the months except July, August and September (Fig.8). The positive trends were contributed principally by the summer harvest crops (wheat as the main crop), while the negative trends were mainly contributed by the autumn harvest crops (maize as the major crop). Regressive analysis showed that the downward trends of GPP in summer season were resulted from the significant declines of monthly sunshine duration and radiation (r=0.38 to 0.57 from June to August, p<0.05).

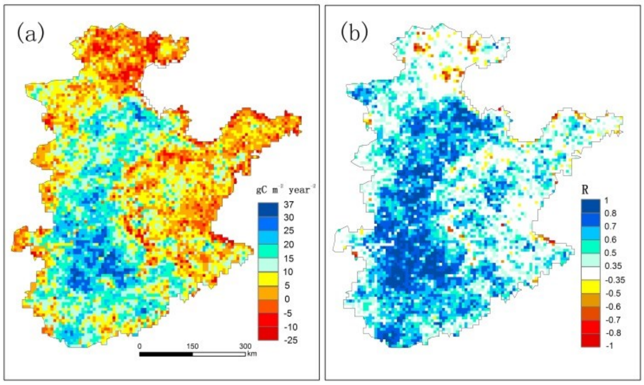

Fig.7 (a) Spatial distribution of GPP trends and (b) Pearson coefficients of trend at p<0.05 significant level.

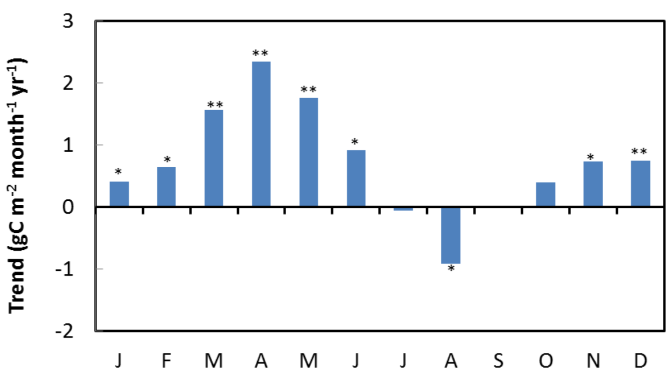

Fig.8 Monthly trend of GPP from 1981 to 2013 (Significant levels: * is p<0.05; **is p< 0.01).

3.2.3 Evapotranspiration (ET)

Water loss from the vegetation surface as ET is directly regulated by atmospheric vapor demand and leaf stoma physiologically functioning (Buckley & Mott, 2013). Inter-annual variation of ET is controlled by climate variability/change and agronomical managements. Generally potential ET ($ET_{p)}$ is used to represent the available energy for water vaporization on land surface. As shown in Fig.8a, ET_p was slightly decreasing over the plain during the last three decades, resulted from offsetting among the effects of reduced global radiation, declining wind speed and increasing water vapor deficit (Song et al., 2009); simultaneously,

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actual ET was predicted to be slightly increasing (p<0.05), consistent with the enhancement of greenness. It was noticed that the evolutions of potential and actual ET coincided with the hypothesis of complementary relationship. At monthly scale, ET was significantly increasing from February to April, but it was decreasing in August (Fig. 8b). This implicates that climate warming may be beneficial to spring crops by waking wheat recovering early from dormancy, whereas decline of net radiation (R_n) (especially in August, significant level p<0.001) may lead to the downward tendency of ET rates in summer.

Over the whole plain, spatially averaged actual ET and transpiration were 627±162 mm yr^{-1} (about 92% of annual precipitation) and 416±129 mm yr^{-1} (about 67% of ET), respectively. The trend of annual ET ($p<0.1$)with CV (coefficient of variation) of 0.05 was 0.88 mm yr^{-2} from 1981 to 2013, which was less significant than that of NDVI (p<0.01). Decadal ET amounts in 1980s, 1990s and 2000s were 610, 626 and 640 mm, respectively, corresponding to the slightly rising trend of precipitation. It is found that GPP increased with higher significant level thant that of ET, implicating the enhancement of water productivity in the plain. Spatially, the trends of ET were positive over 86.0% of the study region, distinguishing in the mid and southern parts, while negative trends were mostly occurred in the northern part (Fig.9(a, b)), which was consistent with the pattern of GPP tendencies. By using a water balance model, Zeng et al. (2014) also presented an increasing trend of ET over the North China Plain from 1982 to 2009.

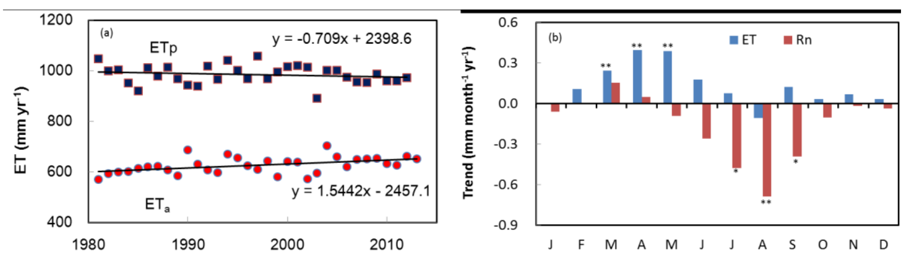

Fig.9 Inter-annual trends of potential and actual annual ET (a) and trends of monthly ET and net radiation (R_n) (b) from 1981 to 2013 (Significant levels: * is p<0.05; **is p< 0.01).

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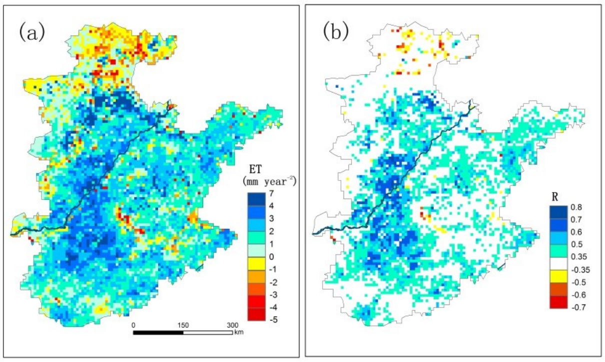

Fig.10 (a) Spatial distributions of ET trends, and (b) their temporal Pearson coefficients above *p<0.05* significant level from 1981 to 2013.

3.3 Contributions of climate change, atmospheric CO_2 fertilization and agronomical management to changes of ET and GPP

3.3.1 Spatial patterns of the contributions

The contributions from climate change, atmosphere CO_2 enrichment fertilization and agronomical management illustrated considerably spatial heterogeneity for both ET and GPP (Fig.11). Over the whole plain, climate change was exerting positive impact on water vapor exchange from land surface to the atmosphere (f_1), especially in the eastern hilly part where precipitation was increasing slightly. As general knowledge, air CO_2 enrichment stimulates the crop leaf stomatal closing and then reduces transpiration, but its fertilization effect enhances photosynthetic rate and water use efficiency (Buckley and Mott, 2013). Descriptions of the separated effects were presented as following:

The climate change has intensified ET rate almost in the whole area, resulting in 0 to 4 mm increment per year. The effect of climate change was much stronger in the mid to eastern zones with high crop productivities, contributed mainly by air temperature increasing. The contribution of CO_2 enrichment on ET is negative in most areas, ranging from 0 to -1 mm per year. The attributions of agronomical practices and technological advancement represented by LAI increase are somewhat complex, namely remarkable increase ranged from 0 to 6 mm per

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year in the mid-western area where irrigation facilities and soil conditions have been ameliorated greatly in the recent decades through land consolidation, de-salinization. Renewal of cultivars and improved agronomical practices also contributed to the ET intensifying (Zhang et al., 2011). On the contrary, the grids with expansions of built-ups contributed to negative trends of ET, relating to urbanization and land use changes.

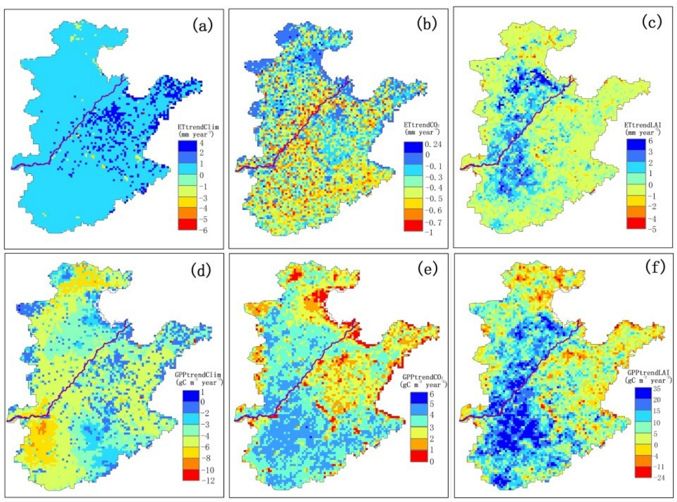

Fig.11 Contributions of climate changes, CO_2 enrichment and management on ET (a, b, c) and GPP (d, e, f) respectively (a and d are for climate; c and e for CO_2; c and f are for management)

Annually, contribution of climate change to GPP is negative, ranged from 0 to -12 gC m^{-2} per year. Lower rates were occurred in the southwestern and northern parts. Air warming and heat waves, declines of precipitation and global radiation are the main causes of crop production reduction (Lobell et al., 2011; Guo et al., 2014). In addition, the spatial variability of climate change effects are associated with the relevant land use/cover and cropping systems. In the hilly areas (western and mid) and eastern coast areas, negative effects were slight, where air warming and air pollution were relatively weak. CO_2 enrichment effects were positive over the whole plain, ranged from 0 to 6 gC m^{-2} per year. It was noticed that the higher effects were associated with higher cropland with favourable irrigation and high productivity, while the lower rate was related with low productivity croplands and natural vetetation communities. Similarly, the effects of human activities on ET were positive in the

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mid to western areas, ranging from 0 to 35 gC m^{-2} per year, associated with croplands of high productivity. The negative effects were mainly occurred in the eastern and northern parts where there is remarkable expansion of urban and dwelling built-ups in the study period.

3.3.2 Regional averaged contributions

On the aspect of regional average, some characteristics of the contributions to water and carbon assimilation are revealed. As shown in Fig.12(a), the contributions of climatic variable change (f_1), elevated atmospheric CO_2 concentration (f_2) and agronomical management (represented by leaf area index (LAI) increment) (f_3) and their interactions to the long term trend of ET were positive, while the contribution of elevated atmospheric CO_2 is negative in the last three decades. It was shown that the contribution of climate change was less than that of agronomical improvement. The relative direct contributions of climatic change, CO_2 fertilization and agronomical management and technologic advancement to evapotranspiration long term trend are 56, -28 and 68%, respectively. Compared with the contributions of direct effects, the relative contributions by their interactions were low (the cumulative effect of f^{12}, f^{13}, f^{23} and f^{123} was only about 4%). Although the global radiation reaching ground was diminished by higher aerosol concentration and deteriorated pollution in the atmosphere (Che et al., 2005), its negative effect on terrestrial ET was offset by the positive effects of air warming and higher vapor pressure deficit (VPD) on ET at annual scale. Reduction of transpiration by enriched atmospheric CO_2 caused by closure of plant leaf stomata at high CO_2 concentration for both C3 and C4 plants may mediated the extra water demand by air warming. The dominant contribution was from the renewal of cultivars and improvement of agricultural techniques and management. In the study period, agronomical management has greatly improved, including the establishment of irrigation facility, prevalent uses of chemical fertilizers and pesticides. For example, irrigated area in the northern part (mainly Hebei Plain) has increased by 2.5 times, and chemical synthetic fertilizer input has increased about four times, consequently, crop grain production has enhanced about two times from 1980s to 2000s(Xu et al., 2005). Climate change and management improvement (Irrigation practice, synthetic fertilizers supply and new cultivars adoption) are the main

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contributors of ET intensifying over the plain.

As shown in Fig.12(b), the enriched atmospheric CO_2 fertilization and agronomical management improvement presented a positive contribution to GPP trend during the study period. It was somewhat out of expectation that the contribution of climate change to GPP was negative at annual scale. The relative contributions of climate change, CO_2 fertilization and management to the vegetation GPP enhancement were -32, 25 and 103%, respectively, which demonstrated that the improvement of agricultural management was the dominant driver to GPP increasing in recent decades. The positive effects on GPP were associated with human activities and natural factors, such as input of synthetic fertilizers and atmospheric nitrogen deposition, irrigation and other agronomical technology improvement, as well as fertilization of enriched atmospheric CO_2. The negative contribution by climate change was mainly happened in summertime (Fig.8). Since there was less benefit of CO_2 enrichment to summer maize (C4 type), the reduced maize productivity due to global radiation decline was not fully offset. Some researches, such as Piao et al. (2015) also reported that climate change was exerting negative impact on the vegetation greening trend in the northern part of NCP (including Hebei, Beijing, Tianjin Districts); Liu et al. (2010) attributed the reduction of crop productivity over the NCP to shortening of vegetative growth length under climate warming. As shown in Fig.4b, it was illustrated by NDVI time series that greenness in summer season was quite stable; however it is significantly increasing in spring and autumn seasons, indicating that climate warming was beneficial for crop growing in the cool seasons. In addition, carbon assimilated by summer crops was larger than that in spring. Thereby, the sign of GPP annual trend was determined by the trend in summer season. As air temperature increasing was not so detrimental to maize growth in summer season yet, the decline of downward shortwave radiation was considered to be responsible for GPP decline.

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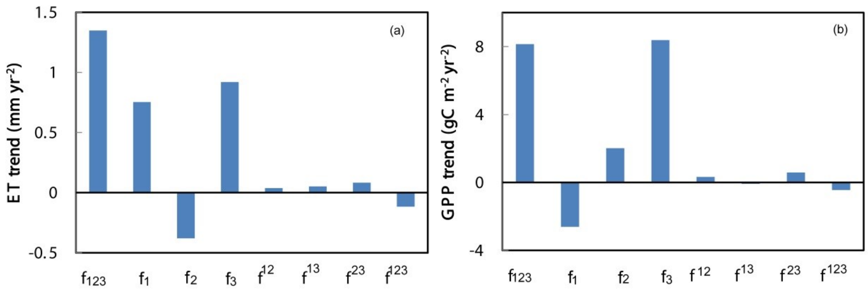

Fig.12(a) Contributions of climate change, atmospheric CO_2 enrichment and agronomical management to ET and (b) contributions to GPP trends

3.3.3 Effects of climatic variables on monthly ET and GPP trends

To attribute the responses of cropping systems to the trends of single climatic variables, the VIP model is used to diagnose the effects of climate change on ET and GPP at Beijing meteorological observation site. The contributions of a single variable to the trends of ET and GPP are expressed by their differences simulated with the current and de-trended variables respectively. Here only the climatic variables of radiation, air temperature and wind speed are linearly de-trended at monthly scale, since no significant trends of precipitation and humidity are detected. As shown in Table 2, while the global radiation was de-trended, the negative correlation coefficient of monthly GPP with time was reversed from negative to positive in springtime, and from significant ($r <-0.6$, $p<0.01$) to insignificant levels ($r<-0.15$, $p>0.01$) in July and August. It was affirmed that the decline of global radiation was the dominant factor for reduction of crop GPP in summer period (June to August), but in autumn season the changes of radiation, temperature and wind speed were all responsible for GPP changes. From Table 2, it could be deduced that the effects of temperature rising on crop productivity was positive and significant in spring (March and April) and autumn (September and October), whereas its effect was weak in summer (May to August). It was noticed that the effect of radiation change was quite weak in March, when no significant trend of shortwave radiation was detected. In spring season sunshine durations were increasing from 1980s to 2010s (Wang and Yang,2014). In June, except global radiation, changes oftemperature and precitpitationhave contributed to GPP increasing. Additionally, fertilizing effect of enriched CO_2 on C3 crop is a critical driver to GPP increasing. However, since the maize as C4 crop does not benefit much from atmospheric CO_2 enrichment, new cultivars with higher light use efficiency should be adopted to sustain the maize productivity under declined global radiation condition resulted from exacerbating aerosol concentration and air pollutions.

Comparatively, the effect of climatic change on ET was less significant than that of vegetation GPP. The model simulations showed that ET enhanced by air temperature rising was mainly occurring in August to October, while the effect of solar radiation decreasing was detected from June to September in the maize growing period.

Table 2 Monthly Pearson correlation coefficients of GPP trends (r_ALL: all variable are not de-trended；r_R: radiation is de-trended；r_T: air temperature is de-trended; r_R-T-U: radiation, temperature (T) and wind speed (U) are all de-trended).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
r_ALL	0.17	0.14	0.36	0.31	0.25	-0.16	-0.56	-0.37	-0.75	-0.48	-0.19	-0.03
r_R	0.29	0.15	0.38	0.40	0.23	0.49	-0.15	-0.07	-0.67	-0.46	-0.18	-0.03
r_T	0.11	-0.06	0.02	0.09	0.30	0.05	-0.64	-0.30	-0.48	0.08	0.08	0.05
r_R_T_U	0.10	-0.05	0.00	0.11	0.33	0.35	-0.20	-0.08	-0.13	0.10	0.09	0.06

4 Discussion

Our simulations suggested that annual ET and vegetation GPP were increasing over the North China Plain during 1981 to 2013. Climate change contributed positive to ET intensification, but it contributed negatively to GPP enhancement. Agronomical management and technological advancement are the dominant factor to promote GPP increasing. The use of remote sensing NDVI series have greatly improved the reliability of the vegetation water consumption and productivity prediction at spatial and temporal scales, even if there were uncertainty in vegetation characteristics retrievals from NDVI dataset. The results were supported and consistent with most relevant studies at field and regional scales.

4.1 Is the trend of ET upward or downward over the NCP?

Although the crop productivities are steadily increasing, whether the actual ET over the NCP is increasing or decreasing during the last three decades is controversial from the reported literatures. By using the complementary relationship models (Brutsaert and Stricker, 1979), actual ET and potential ET both were decreasing (Cao et al., 2014; Gao et al., 2011). However, ET was increasing predicted by the process - based VIP model from 1981 to 2013, which was in consistent with the increasing trend of terrestrial greenness (Wang et al., 2016). Yuan and Shen (2013) found that in the Northern part of NCP (Hebei Province) ET was positively correlated with crop grain yield and agricultural water use was increasing from 2004 to 2008. Field measurements under well - watered fields also showed that seasonal ET rates of both winter wheat and summer maize were increasing (Zhang et al., 2011). Bruatsaert (2006) acknowledged that decreasing pan evaporation was an evidence of increasing terrestrial evaporation. As general knowledge, the sign of ET change should be the same as that of vegetation greenness. Over the NCP a positive trend of ET was more believable, in the light of significantly increasing NDVI over the growing season, especially in spring. The positive effects of warming with higher water vapor deficit on ET might be offset by the negative effect of declining solar radiation and wind speed on potential evaporation. On viewpoint of the complementary relationship hypothesis (Hobbins et al., 2001), alteration of available energy partitioned into latent heat flux (or ET) is dominated by the atmospheric water vapor deficit. Namely, while more vapor is evaporated into the atmosphere boundary layer, its water vapor deficit is correspondently relaxed, resulting in a lower rate of ET_p. However, while declining global radiation being the dominant factor to ET trend, actual ET (ET_a), wet surface ET (ET_w) and potential ET (ET_p) are all tracing the trend of available energy (net radiation). In the study period, net radiation was declining with a rate of -5.58 MJ yr^{-1} (r=0.56, p<0.01) over the NCP. As the trends of both ET_p and ET_w were dominated by the radiation trend in the NCP, then ET_a estimated from the complementary relationship was definitely following the negative trend of radiation, because the positive trend of aerodynamic evaporation was weak as a tradeoff of positive effect of rising water vapor deficit and negative effect of decreasing wind speed. However, the declining ET trend resulted from the reduced radiation has actually been reversed by increasing green leaf area, which would reduce land surface albedo and temperature, etc. Consequently, ET and GPP were showing slightly increasing. This study case also confirmed the limitations of the complementary relationship for assessment of evaporation trend under the condition of radiaiton declining.

4.2 Effects of climate change and CO_2 on the cropping systems

Without adaptation measures, climate change is illustrated to exert negative effects on the productivity of cropping system in the NCP during the last three decades (Mo et al., 2013; Liu et al, 2010). Changes of individual climate variables affected differently on specific cropping systems, associated with crop type and growing season. Climate warming in winter and spring seasons was benefit to vegetative growth of winter wheat (Mo et al., 2013). Although air warming has shortened the growing length, the autonomously adopted cultivars with higher thermal requirement usually maintained the crop growth length and accumulated more photosynthesis product, which may outweigh the extra respiration consumption under warmer climate (Wang et al., 2010). So far as, the effects of global warming on wheat production were inhomogeneous in the North China Plain, which were positive in the northern part but negative in the southern part (Zhang et al., 2013). The reasons are that during the wheat growth period air temperature is still below the favorable conditions in the high latitude part of the plain, thereby recent global warming is benign to the wheat growth, however, the air warming may be detrimental in the southern part, especially for rainfed wheat (Xiao and Tao, 2014).

However, dominated by summer monsoon in the North China Plain, climate is hot in summer maize growth period. Due to maize is tropical originated species with high thermal requirement, it can tolerate relative high air temperatures. Our study showed that it was not sufferred noticeably from air warming in the recent decades, confirmed also by Xiong et al. (2012). However Guo et al. (2014) reported that effect of air warming on maize was adverse with an Agro-Ecological Zones model and the decreased daily temperature range (DTR) may be detrimental to crop yields. Currently, adaptation measures may boost the production, such as harvest time delay (Wang et al., 2014) or planting date advancement (Sacks and Kucharick, 2011) .

As increase of atmospheric aerosols by industrial production and combustion, global radiation has declined in many parts of the world, in which direct component decreased but diffuse component increased, so called “global dimming” (Liepert, 2002; Ren et al., 2013). The decline of global radiation has resulted in less pan evaporation and carbon assimilation in crop and natural vegetation communities (Xiong et al., 2012; Xiao and Tao, 2014), nevertheless plant canopies can use the diffuse radiation with higher efficiency than direct beam (Gu et al., 2002). In spring time, while the atmospheric circulation is shifting from continental to ocean monsoon in East Asia, the wind speed is relative high and consiquently air pollution and aerosols are usually low, thereby global radiation is not reduced obviously in the wheat growth period (Table 1), illustrating that air warming and precipitation variability other than radiation decrease are the principal climate factors contributing to the tendency of wheat production. In constrast, global radiation decline significantly in summer season in the North China Plain (Table 1), as a result, productivities of autumn harvest crops such as maize are mainly affected. For example, Guo et al. (2014) reported that maize potential productivity was reduced by 20 kg hm^{-2} due to global radiation decline in the last decades over China.

During the study period of 1981 to 2013, atmospheric CO_2 concentrention increased from 340 to 396 ppm, which contributed to enhancement of crop productivity. However, most studies with statistical analysis models neglected the contribution of CO_2 fertilization (e.g., Lobell and Burke, 2010; Song et al., 2014). As confirmed by FACE experiments, elevated atmospheric CO_2 concentration is accelerating plant photosynthesis and reducing transpiration, whose fertilizer effect is 0.065% per ppm increase for C3 plants (Field et al., 1995; Long et al., 2006; Ainsworth et al., 2008). In our simulations, the contribution of CO_2 to GPP was positive while to ET was negative. The positive CO_2 effect on GPP almost compensates for the negative effects of climatic variable changes. However, we should bear in mind, as Ainsworth et al.(2008) pointed out that the CO_2 fertilizer effect may be over-estimated by the process-based crop/ecosystem models.

4.3 Effects of agronomical practice and technique advancement and other factors

Remotely sensed NDVI is an excellent indicator for long term changes of vegetation covers. Here we assumed that climate change did not modify the tendencies of vegetation covers, but dominated its inter-annual variation. Renewal of crop cultivars, applications of synthetic fertilizer and irrigation, as well as conservancy tillage and nitrogen deposition are all contributing to the crop and/or natural productivity improvements (Yu et al., 2012; Bai et al., 2015; Piao et al., 2015). National statistical records of grain yields at county scale showed rapid increase from 1980 to 1990, and moderate increase in 2000s. Enhancement of crop yields was mainly stemmed from more biomass accumulation and higher harvest index than previous varieties (Zhang X. et al., 2013). In our simulations the upward trend of GPP was more significant than that of ET, which was in consistent with the increasing trend of cumulative NDVI. Agronomical practices and technology advancement contributed to 103% GPP changes in our study. By using crop models, Yu et al. (2012) and Song et al. (2014) reported relative contributions of 92% and 62% by agronomical management and renewal of cultivars for rice respectively, and Guo et al. (2014) presented that 99.6 to 141.6% maize yield increases was contributed by technological advancement in China since 1980s. The previous studies showed, if no adoption measures were taken, climate change generally contributed negatively to crop productivities in the mid-latitude areas, but the negative effects were usually compensated for by genetic improvements, applications of fertilizer and irrigation, pest and weed control, as well as CO_2 and nitrogen deposition effects (Liu et al., 2010; Lobell et al., 2011; Guo et al., 2014; Bai et al., 2015). Under warming climate condition, it is expected that water requirement by crops and natural plants will increase, but the intensified ET may be limited by insufficient soil moisture availability. Therefore, the sustainability of crop productions are greatly depending on the improvement of agronomical management and technological advancement on varietiy breeding.

5. Summary and conclusions

Climate change and human activities have greatly altered the hydrological regime and crop productivity in the North China Plain with warm temperate climate during the recent three decades. The VIP ecological model integrated the NOAA-AVHRR NDVI data series predicted that spatial average annual actual ET was weakly increasing while vegetation primary productivity (GPP) was significantly increasing (p<0.01) from 1981 to 2013, being consistent with remotely sensed NDVI trend. The increases of actual ET and GPP were mainly occurred in spring season, while ET and GPP were obviously decreasing in August owing to global radiation diminishing.

Climate change, elevated atmospheric CO_2 fertilization and agronomical management all contributed to the inter-annual trends of ET and crop GPP. The relative direct contributions of climatic change, CO_2 fertilization and agronomical management to ET increasing were 56, -28 and 68%, while the contributions to GPP were -32, 25 and 103%, respectively. Air warming intensifies the crop water requirement and enhances the production of crops harvested in summer. The decline of global radiation resulted from exaggerated aerosol concentration and air pollutions was considered to be the main cause of GPP reduction in August. The study confirmed the necessary for imminent control of air pollution and aerosol to sustain the agriculture system productivity.

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