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Climate, agricultural production and hydrological balance in the North China Plain

Enli Wang,[a]* Qiang Yu,[a,b] Dingrong Wu[b] and Jun Xia[b]
[a] *CSIRO Land and Water, Canberra, ACT 2061, Australia*
[b] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*

ABSTRACT: The North China Plain (NCP) is the largest agricultural production area in China. The extensive use of groundwater for irrigation agriculture under variable climatic conditions has resulted in the rapid decline of the groundwater table especially in areas north of the Yellow River, leading to hydrological imbalance and unsustainable agricultural production. This article analyses the sustainable level of vegetation/crop water use under the NCP climate by mimicking the evapotranspiration of a natural forest ecosystem. Such a system would have a mean annual evapotranspiration ranging from 470 mm/year in the northern to 910 mm/year in the southern part of the plain, leading to a mean annual water excess (rainfall minus evapotranspiration) ranging from 21 to 124 mm/year. The natural forest ecosystem would use less water than the current wheat/maize double cropping system. To mimic the water use of the natural system, dryland farming has to be practiced, and wheat and maize crops would have a water deficit of 90–435 and 0–257 mm/year, respectively. Under average conditions, this would mean that all the areas north of the 36°N line have to abandon winter wheat production. Stopping irrigation will lead to significantly lower wheat yields (average yield 0.8 t/ha in the north to 5.2 t/ha in the south) and increased variability in wheat and maize yield both interannually and spatially. Better management practices, such as opportunity cropping (what and when to crop depending on climate and soil conditions rather than a set annual cycle), better use of climate forecast information to direct decision making, are required in order to achieve maximum return in good years while minimising cost in bad years. Analysis on rainfall and potential evapotranspiration (PET) from 1961 to 2000 shows that there has been an increasing trend in crop water deficit in the northern part, but a decreasing trend in the southern part of the plain. It remains to be further studied whether this reflects long-term climate change or only a part of the climate variability. Copyright © 2008 Royal Meteorological Society

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1. Introduction

The North China Plain (NCP), the largest agricultural production area in China, provides more than 50% of the nation's wheat and 33% of its maize production (State Statistics Bureau, 1999) with a currently dominant wheat/maize double cropping system. The NCP is characterized by a summer monsoon climate with concentrated summer (July–September) rainfall. Annual rainfall declines from southeast to northwest. As a result, there is a significant decrease in crop yield and increase in interannual yield variability from southeast to northwest under rain-fed conditions, especially for wheat crop. However, such spatial and temporal variability in crop yield has been largely reduced by increased irrigation, leading to high and much stable crop production in most areas, which has put the NCP in an ever-important position as a grain production base for the nation.

Irrigation agriculture accounts for around 70–80% of the total consumption of water resources in the NCP (Liu *et al*., 2001; Xu *et al*., 2005), most of which comes from groundwater. Increased irrigation water use in the northern part of the plain has changed the hydrological balance significantly, causing rapid decline of the groundwater table (Zhang and Zhang, 1995; Foster and Garduno, 2004). This has raised serious questions about its impact on the sustainability of water resource and agricultural production (Liu *et al*., 2001).

To reduce agricultural water use, studies have been carried out on water-saving management measures including better engineering for water conveyance, management and agronomic measures for improved irrigation efficiency (Yang *et al*., 2003; Foster and Garduno, 2004), enhanced pricing mechanism, policy and institutional reforms (Yang *et al*., 2003). However, due to the big gap between available rainfall provided by the monsoon climate and water demand of the wheat/maize cropping system, any attempts to meet the crop water deficit by irrigation from groundwater will cause continuous decline of the groundwater table (Kendy *et al*., 2004).

* Correspondence to: Enli Wang, CSIRO Land and Water, Canberra, ACT 2061, Australia. E-mail: Enli.Wang@csiro.au

In the end, reduction in agricultural water use, at the cost of reduced grain production, becomes the unavoidable option (Kendy *et al*., 2004; Xu *et al*., 2005).

A major part of the water and agricultural problems in the NCP arises from the altered hydrological balance due to changes in agricultural production systems. Mitigation of the environmental impact of current agricultural systems requires restoration of the hydrological balance to its previous sustainable state. The question is: what is a sustainable state of water balance for farming systems in order to maintain a regional hydrological balance under the variable climate?

This article attempts to examine the sustainable level of agriculture water use for a sustainable hydrological balance, and what it means for agricultural production under variable climate. First, we define and estimate the sustainable level of water use through mimicking a natural ecosystem. We then estimate the crop water deficit under the sustainable level of water use, and assess the level of crop production that can be supported by available water resources. Finally, we investigate changes in crop water deficit and yield as affected by temporal and spatial climate variability.

2. Materials and methods

2.1. Study region and historical climate data

The NCP (114–121 °E, 32–40°N) covers an area of 320 000 km^2 (Figure 1) with a population of more than 200 million. It has a cool to warm temperate monsoon climate with annual rainfall ranging from 470 mm in the north to 910 mm in the south (Figure 2(a)). Wheat/maize double cropping rotation is the dominant cropping system in most parts of the plain. While the concentrated summer rainfall favours maize growth, frequent spring drought imposes severe water stress to wheat crop. Forty years (1961–2000) of daily climate data from 32 stations uniformly distributed in the NCP (Figure 1) were obtained from the Bureau of Meteorology, China, and used in this study. They include maximum and minimum temperatures, sunshine hours, humidity and wind speed. Solar radiation is not available for most of the stations. The Angstrom equation was used to calculate the daily global solar radiation with sunshine hours with $a = 0.18$ and $b = 0.55$ as follows:

$$R_s = \left(a + b\frac{n}{N}\right) R_a \tag{1}$$

Where R_s is the solar radiation (MJ/m^2/d); n and N are the actual and maximum durations of sunshine (hour); R_a is the extraterrestrial radiation (MJ/m^2/d). N and R_a can be calculated from latitude and time of year (Allen *et al*., 1998).

2.2. Definition of sustainable level of water use and sustainable water balance

It has been suggested that natural systems can serve as models for the design of sustainable systems of land use (Ewel, 1999; Hatton and Nulsen, 1999; Lefroy *et al*., 1999a,b). Ewel (1999) used the 38 life zones classified by Holdridge (1947, 1967) to divide climatic regions into four categories for agricultural suitability. Based on the classification of Holdridge (1947, 1967), the NCP would have moist to dry forest as natural vegetation. It falls

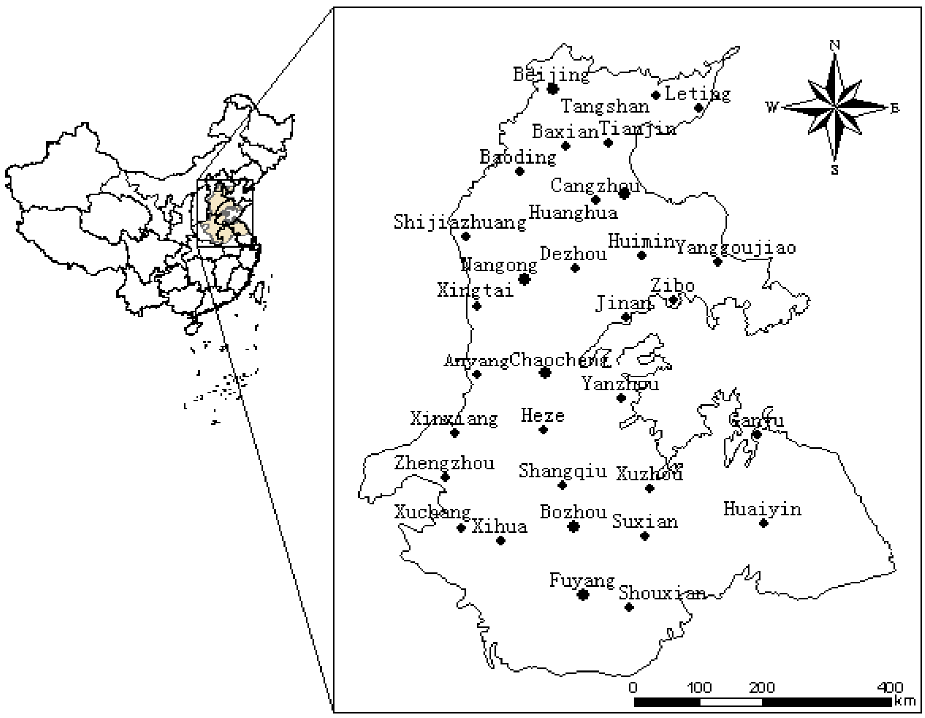

Figure 1. The North China Plain and the locations of meteorological and experimental stations used in this study. This figure is available in colour online at www.interscience.wiley.com/ijoc

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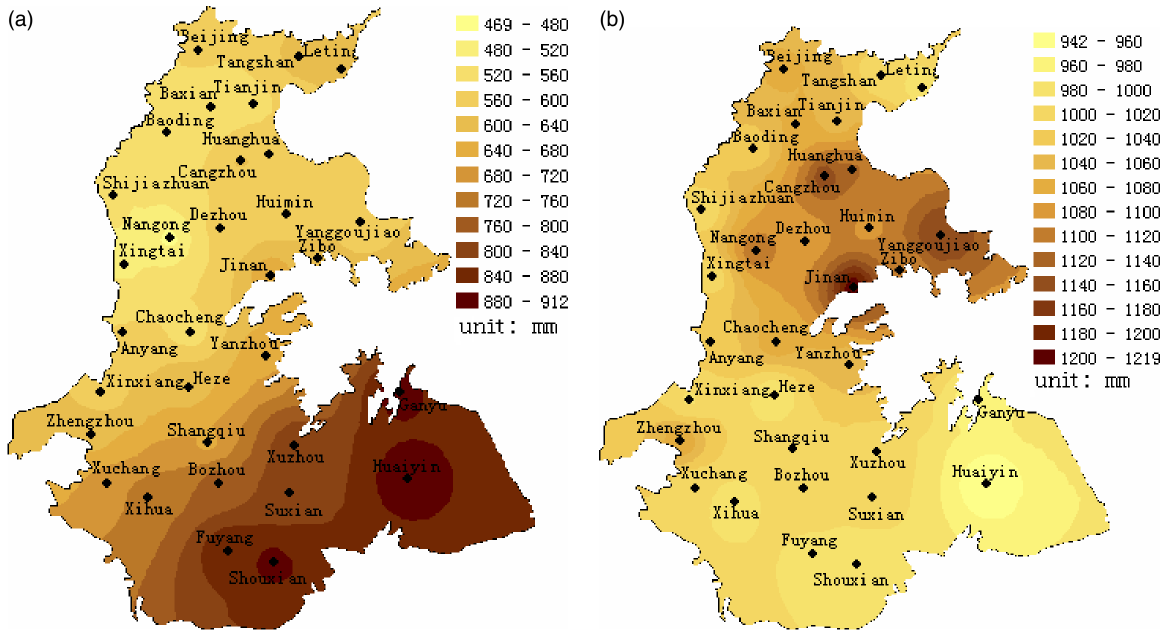

Figure 2. Mean annual rainfall (a) and potential evapotranspiration (b) (mm/year) in North China Plain based on climate data from 1961 to 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

close to the best region for agriculture as identified by Ewel (1999). Thus, the sustainable state of water balance is assumed as water balance of a natural forest system.

The evapotranspiration of the natural forest system (E_F) represents the sustainable water use. It is assumed that any farming systems have to mimic E_F for long-term sustainability and sustainable hydrological balance. Under such conditions, the water excess for surface runoff and groundwater recharge is calculated as the difference between rainfall and E_F.

2.3. Estimation of water balance terms under a sustainable state

For a given site, water balance over a long time period (40 years in this study) can be written as:

$$Q = R + D = P - E \tag{2}$$

where Q represents the water excess, P is precipitation, E is evapotranspiration, R is runoff and D is drainage below the plant root zone. The unit of all variables is millimeter per year (mm/year). For long-term average, the change in soil water storage (ΔS) is neglected (Zhang *et al.*, 2001). In the semi-arid and sub-humid environments like the NCP, E will generally make up the largest fraction of P. The relative balance between R and D is strongly influenced by soil surface and subsurface properties and rainfall intensity.

For catchment water balance modelling, Zhang *et al.* (2001) derived a simple model for estimation of long-term catchment-scale evapotranspiration based on earlier work (Budyko, 1958; Milly, 1994; Choudhury, 1999; Koster and Suarez, 1999) and data from over 250 catchments worldwide. This model is able to predict evapotranspiration worldwide with an error of 6% (Zhang *et al.*, 2001). It has also been found to be applicable to point scale studies (Keating *et al.*, 2002; Wang *et al.*, 2006a). It is used here (Equation (3)) to estimate the average evapotranspiration of natural vegetation (E):

$$E = P\left(\frac{1 + w\dfrac{E_M}{P}}{1 + w\dfrac{E_M}{P} + \left(\dfrac{E_M}{P}\right)^{-1}}\right) \tag{3}$$

where w is a fitted plant available water coefficient. Typically $w = 2.0$ for forest (Zhang *et al.*, 2001). w also varies with rainfall seasonality (Keating *et al.*, 2002; Wang *et al.*, 2006a). E_M represents the potential evapotranspiration (PET) used in the model. Zhang *et al.* (2001) parameterized the model with a fixed value of $E_M = 1400$ mm/year for forests. These parameter values are used to calculate evapotranspiration E_F (Equation (3)) and the water excess Q_F (Equation (2)) for a natural forest as the water balance terms under the defined sustainable state (Figure 3).

2.4. Calculation of water balance of the wheat/maize double cropping system

A simple approach is used to estimate the water balance of the wheat/maize double crop rotation. The growing seasons of wheat and maize was set as the period from 1 October to 31 May and from 1 June to 30 September, respectively. Due to the decreasing temperature from south to north, the length of crop (both wheat and maize) growing period increases with latitude. It is assumed that the growing period of wheat will be shortened by up to 1 month, while that of maize by 2 weeks from the northernmost to the southernmost locations in the NCP. These assumptions are based on past and local

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experiences. In reality, a longer season maize variety can be chosen in the south, which is not considered here.

The water demand or PET of wheat and maize, i.e. the crop evapotranspiration under standard conditions as defined in Allen *et al.* (1998), was calculated based on the method recommended by FAO (Allen *et al.*, 1998). The reference evapotranspiration (E_0) was calculated daily and summed to get the total for the whole year (Figure 2(b)), the wheat and maize season respectively. A whole season crop coefficient (K_C) was multiplied to the total seasonal E_0 to calculate the crop PET (Figure 4, 6(a)). The crop coefficient (K_C) was set to 0.93 and 1.1 for wheat and maize, respectively, according to Liu *et al.* (2002); Kang *et al.* (2003) and Allen *et al.* (1998).

Crop water deficit was calculated as the difference between potential crop evapotranspiration and the evapotranspiration of the natural forest system within the wheat and maize seasons (Figure 5, 6(b)) to reflect the departure of water demand of crops from a natural forest system. E_F was partitioned into E_{FW} (October–May) for the wheat season and E_{FM} (June–September) for the maize season. Due to the limited rainfall from October to May, no water excess was assumed during this period, thus, E_{FW} equals total rainfall from October to May, while $E_{FM} = E_F - E_{FW}$.

2.5. Productivity assessment of the wheat/maize system as supported by water availability

Under water-limited conditions, crop yield is determined by available water, rather than temperature and radiation conditions. Bierhuizen and Slatyer (1965) found an inverse relation between crop transpiration efficiency (TE) and vapour pressure deficit (Δe), which was further demonstrated by Tanner and Sinclair (1983), Sinclair *et al.* (1984) and Ehlers and Goss (2003):

$$\mathrm{TE} = \frac{\mathrm{DM}}{T_C} = \frac{k}{\Delta e} \tag{4}$$

where DM is the amount of biomass produced (kg/ha), T_C is the crop transpiration (mm) during the same production period, k is a crop-specific constant (kPa). Under water-limited conditions, crop grain yield (kg/ha) can be simply calculated as:

$$Y = H \cdot \mathrm{DM} = H \cdot T_C \frac{k}{\Delta e} = H \cdot (E_C - E_S) \frac{k}{\Delta e} \tag{5}$$

where H is the crop harvest index–the ratio of the harvest portion to the total above-ground biomass, E_C is crop evapotranspiration (mm), and E_S is the evaporation from soil surface (mm), the part of evapotranspiration not used by the crop.

The harvest indexes of modern wheat and maize has a range of 0.4–0.5 and 0.45–0.5, respectively (Howell, 1990; Sinclair, 1998; Wang *et al.*, 2006b). Due to the narrow range, a constant harvest index value of 0.45 and 0.5 was used for wheat and maize, respectively.

E_S in Equation (5) accounts for 30% of the total crop evapotranspiration in semi-arid and semi-humid regions (Angus and van Herwaarden, 2001; Liu *et al.*, 2002; Kang *et al.*, 2003). However, a minimum value of E_C must be reached before any grain yield can be produced, which has been estimated as 100–110 mm for wheat (French and Schultz, 1984; Zhang *et al.*, 1999) and around 100 mm for maize (Keller, 2005). A value of 110 mm is used here for both wheat and maize. Based on these values, Equation (5) can be rewritten as:

$$Y = \begin{cases} 0.7H \cdot E_C \dfrac{k}{\Delta e}; & \text{if } E_C \geq 110 \text{ mm} \\ 0; & \text{if } E_C < 110 \text{ mm} \end{cases} \tag{6}$$

The crop-specific constant (k) is estimated as 45–60 kPa for wheat (Sinclair *et al.*, 1984; Ehlers and Goss, 2003; Wang *et al.*, 2004) and around 90–120 kPa for maize (Sinclair *et al.*, 1984; Ehlers and Goss, 2003). The values, 55 and 90 kPa, were used for wheat and maize, respectively (Wang *et al.*, 2002). On a daily basis, daytime vapour pressure deficit (Δe) is estimated according to Wang *et al.* (2004).

The potential yield of wheat and maize under full irrigation is calculated using Equation (6) and the potential crop evapotranspiration. This was done for each year (using the mean seasonal vapour pressure deficit calculated from daily Δe) and averaged for the period 1961–2000. For winter wheat, very little water is lost by evapotranspiration during the three coldest winter months (December, January, and February), so the seasonal average vapour pressure deficit was calculated as the mean of Δe for October, November, March, April and May.

The crop yield under rain-fed conditions is also estimated using Equation (6), where E_C is replaced by the minimum of effective rainfall and E_C within the wheat and maize season. Due to the relatively low rainfall in the wheat season, effective rainfall is assumed equal to the total rainfall. In the maize season, effective rainfall is assumed as 90% of total rainfall to account for 10% water loss through runoff and infiltration process, which was based on the estimated water excess for a natural forest in the previous section. It has to be stressed that such calculation, and the same as in the calculation below, ignores the impact of soil water storage at crop sowing time on crop yield, which may lead to underestimation of crop yield under rain-fed conditions, especially for wheat. It also ignores the interception of rainfall by crop canopy, which may lead to overestimation of wheat crop yield, compensating some of the yield underestimation due to ignoring the impact of soil water storage.

The level of crop production under the conditions to maintain the defined sustainable water balance is estimated as the levels of wheat and maize crop yields supported by the evapotranspiration of the natural forest system during the wheat and maize periods, (E_{FW} and E_{FM}) respectively, as calculated using Equation (6). Due to the small difference between natural forest evapotranspiration and the effective rainfall amount in the wheat and maize seasons, there is little difference between crop yields estimated using natural forest evapotranspiration and the rain-fed crop yields estimated using effective rainfall.

2.6. Analysis of the impact of climate variability on crop water deficit and crop yield

Impact of temporal and spatial climate variability on crop yield and crop water deficit is analysed based on variation of rain-fed crop yield and crop water deficit for the wheat and maize seasons from 1961 to 2000. Six stations (Fuyang, Shangqiu, Chaocheng, Nangong, Baoding, and Beijging) along a south–north transect from latitude of 32.92 to 39.93 °N (Figure 1) were selected to carry out the detailed analysis. Spatial and temporal distribution of crop water deficit, rain-fed and irrigated crop yield were shown in Figures 7–9.

To investigate the climate trend from 1961–2000, linear regression analysis for annual and seasonal rainfall and potential crop evapotranspiration was performed against time (year). The regression slopes were displayed in Figure 10 to show the spatial pattern.

3. Results and discussions

3.1. Evapotranspiration and water excess under natural forest cover: equilibrium water balance

The estimated evapotranspiration of a natural forest (E_F) in the NCP would range from 450 to 790 mm/year (Figure 3(a)). The spatial pattern of E_F reflects that of the mean annual rainfall (Figure 2(a)). The lowest E_F would occur at the piedmont plain area ranging from Xingtai, Nangong, Shijiangzhuang to Baoding, and Baxian, corresponding to the area with lowest annual rainfall. The highest E_F would occur in the southeast of the NCP where the rainfall is highest.

Under natural forest vegetation, the mean annual water excess would range from 21 to 124 mm/year (Figure 3(b)). In most areas north of the Yellow River, it would be less than 50 mm/year. In the piedmont plain, it is about 20–30 mm/year. This water excess is the total amount of water available for surface flow and groundwater recharge. The exact partitioning between surface runoff and deep drainage will depend on surface and subsurface characteristics.

The estimated evapotranspiration (E_F, Figure 3(a)) and water excess (Q_F, Figure 3(b)) should provide a benchmark of water use for an agricultural system to be sustainable under the NCP climate. It should be noted that E_F is much lower than the PET (Figure 2(b)). Any agricultural system that has a water requirement higher than E_F will require extra water in addition to rainfall. If this extra water is obtained from a groundwater aquifer, it must be lower than or equal to the natural groundwater recharge. Otherwise, the groundwater table will drop.

Tang *et al.* (2004) described the three sources of groundwater recharge before the 1960s in the northern part of the NCP as: (1) direct infiltration of rainfall, (2) infiltration of surface (river) water, and (3) inflow from older rocks surrounding and underlying the plain. Due to the exploitation of deep groundwater aquifers since the 1980s, and the build-up of dams to store water in the mountainsides, source (2) and (3) become less and less important. Direct infiltration from rainfall has become the only source of recharge to the groundwater (Tang *et al.*, 2004). Under such a situation, water use by agricultural systems may not be allowed to exceed E_F in order to maintain a sustainable hydrological balance.

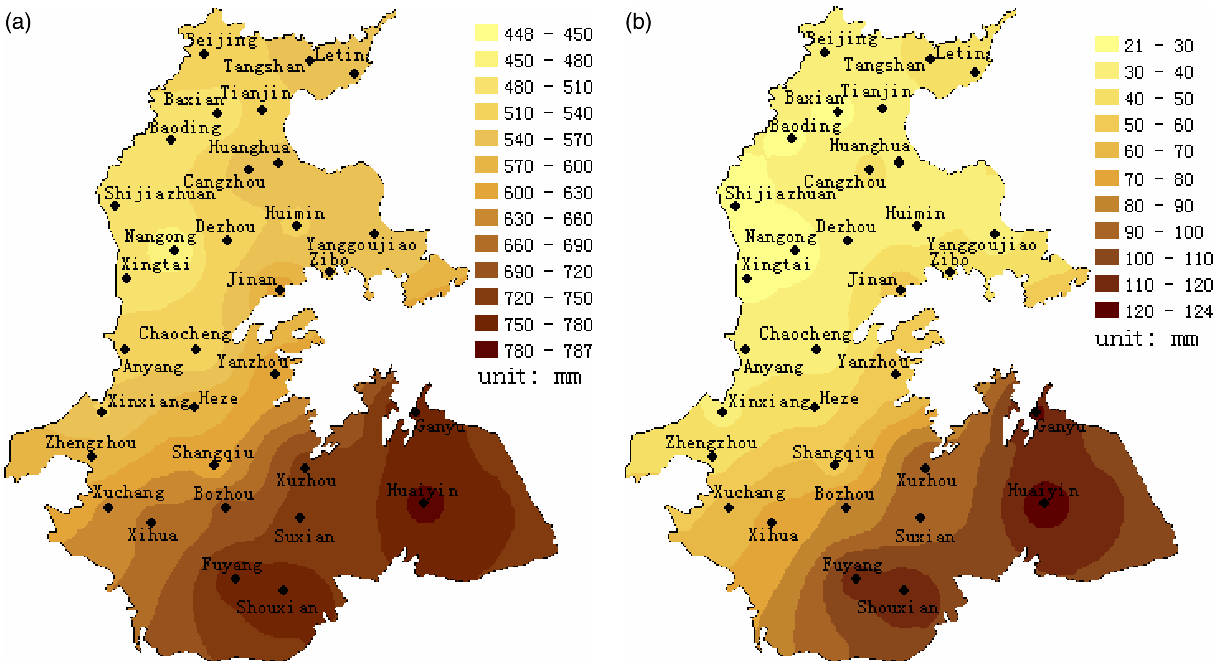

Figure 3. Estimated mean annual evapotranspiration (a) and water excess (b) (mm/year) of a natural forest cover in North China Plain based on mean annual rainfall from 1961 to 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

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3.2. Water balance of the wheat/maize double cropping rotation under the NCP climate

The estimated crop water demand and water deficit for both wheat and maize crops under the NCP climate are shown in Figures 4 and 5 respectively. The changes of crop water demand and water deficit with latitude are shown in Figure 6. In general, for both crops, water demand tends to increase with latitude (Figures 4 and 6(a)), although the maximum water demand is in the region around Huanghua, Cangzhou, and Yanggoujiao. Water demand has a similar spatial pattern to reference crop evapotranspiration (Figure 2(b)), but an opposite spatial pattern to that of annual rainfall (Figure 2(a)). For wheat, water demand ranges from 358 to 550 mm/year. For maize, it ranges from 440 to 585 mm/year. For the two crops, the total water demand is in the range of 800–1100 mm/year (Figure 6(a)).

Due to the declining annual rainfall from south to north, the water deficit of wheat crop increases with latitude (Figure 6(b)) from around 90 mm/year at Shouxian to 434 mm/year in the areas around Beijing. At Shijiangzhuang, the estimated water demand and

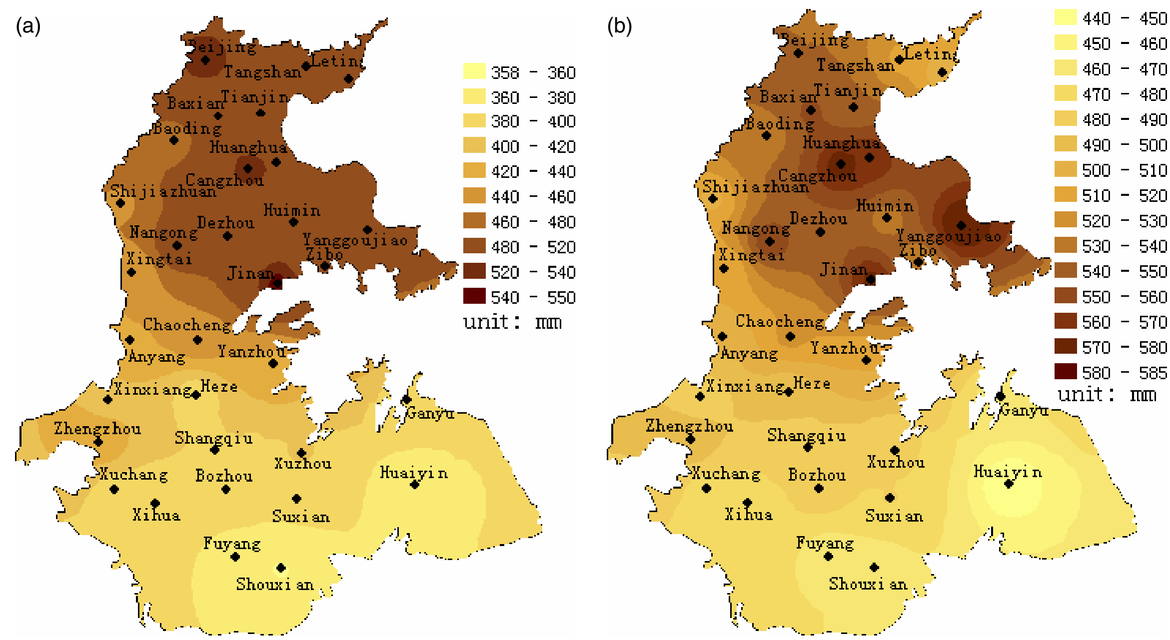

Figure 4. Estimated mean annual water demand (mm/year) of wheat (a) and maize (b) for full irrigation in North China Plain using weather data from 1961 to 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

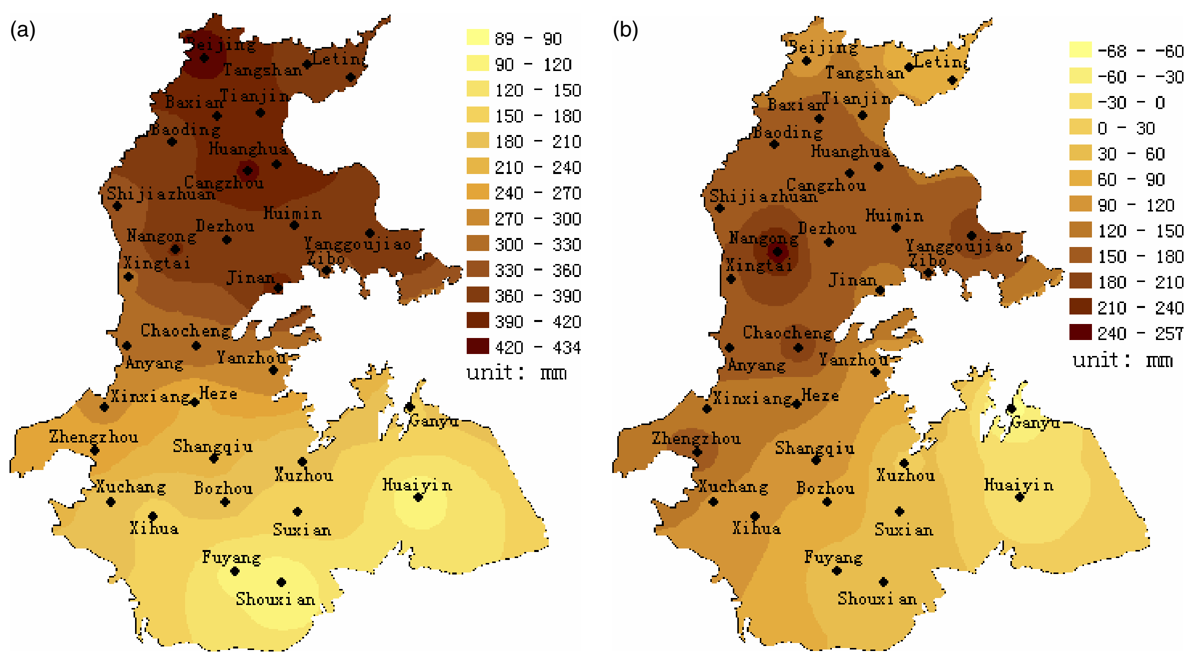

Figure 5. Simulated mean annual water deficit for wheat (a) and maize (b) in a wheat/maize double cropping system in North China Plain using weather data from 1961 to 2000. This figure is available in colour online at www.interscience.wiley.com/ijoc

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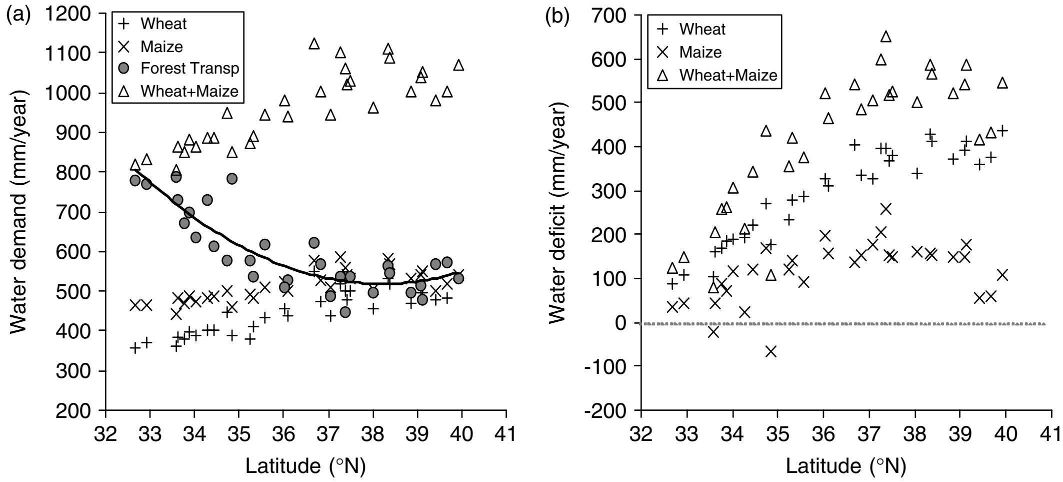

Figure 6. Changes of estimated mean annual water demand (a) and water deficit (b) of wheat and maize crop with latitude (1961–2000). In (a), the solid circles represent the evapotranspiration of a natural forest cover; the solid line is the regression line for forest evapotranspiration. In (b), the grey dashed line indicates zero water deficits.

water deficit of wheat crop are 455 and 350 mm/year, respectively, which are very close to the experimental results (455 mm/year water demand) of Liu *et al.* (2002) at Luancheng County near Shijiangzhuang city. On average, maize crop does not experience water deficit in the southeast corner of the plain. In other areas, maize water deficit ranges from 0 to 257 mm/year with the highest water deficit in the middle areas between 36 and 38°N (Figure 6(b)), the area with lowest rainfall and highest PET.

In the areas with the lowest latitude around Fuyang and Shouxian (the southernmost part), total PET of wheat and maize is very close to that of a natural forest vegetation (Figure 6(a)), which implies that the double cropping system can be sustainable in terms of water balance. However, in the areas with latitude higher than 36–37 °N, the water demand of a single crop (either wheat or maize) is nearly as high as that of natural forest vegetation (Figure 6(a)). If the natural forest system needs to be mimicked, only one crop can be grown. Due to the summer monsoon rainfall in the maize growing season, maize is the most suitable crop to be grown. Winter wheat is not suitable in this northern area unless extra water supply is available. Kendy *et al.* (2003, 2004) and Xu *et al.* (2005) drew the same conclusion in the Hebei plain. Our results further show that under average conditions all the area north to the 36°N line (close to Anyang-Chaocheng line) may need to reduce/abandon winter wheat production in the future for a sustainable hydrological balance. In most areas south of the 36°N line, rainfall is in excess of maize crop water demand, but not enough to support an added wheat crop. Whether a wheat crop can be grown depends on the year type (see discussion below) and availability of extra water supply–either from surface or groundwater.

3.3. Water-supported crop productivity of the wheat/maize double cropping rotation

Wheat and maize crop productivity estimated based on potential crop evapotranspiration and water availability is shown in Figure 7. Under full irrigation when the crop water demand can be met, the estimated wheat yield ranges from 6.9 to 10.2 t/ha; it increases with latitude (Figure 7(a)) due to the longer growing period at higher latitude. Under rain-fed conditions, the estimated wheat yield is much lower in all areas, ranging from 0.6 to 5.2

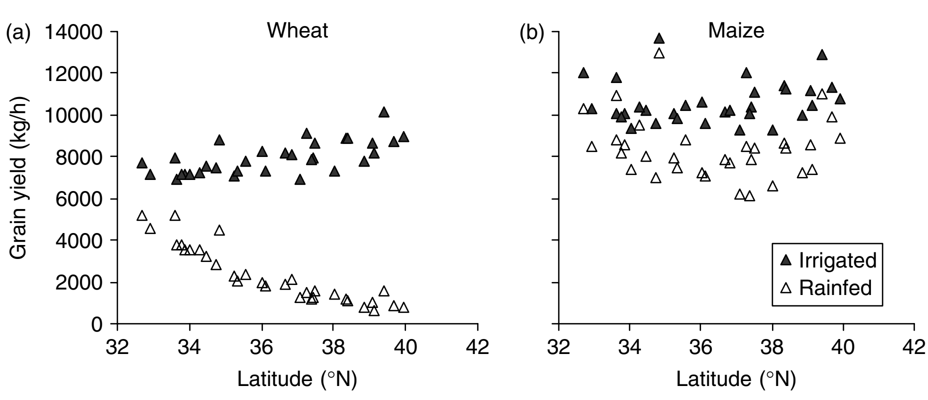

Figure 7. Changes of estimated mean grain yield of wheat (a) and maize (b) with latitude (1961–2000). Impact of stored soil moisture at sowing time was not considered.

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t/ha and decreasing with latitude (Figure 7(a)) due to the declining available rainfall. The estimated maize grain yield under full irrigation ranges from 9.2 t/ha to above 13.6 t/ha (Figure 7(b)). Under rain-fed conditions, maize yield ranges from 6.1 to 13.0 t/ha with the lowest maize yield in the middle of the plain between 36 and 38°N corresponding to the area with lowest rainfall.

The estimated wheat grain yield range and spatial distribution under full irrigation is very similar to the results of Wu *et al*. (2006), but lower than that of Wang and Han (1990) in the south part of the plain, due to differences in the data used and assumptions on growing period change with latitude. Wang and Han (1990) used average climate data from 1961 to 1980 and might not adjust the growing period with latitude. The estimated wheat rain-fed yield is lower than that of Wu *et al*. (2006) and Wang and Han (1990), possibly due to the fact that no soil water storage at wheat sowing time was accounted for in this study. Every 100 mm of extra stored soil moisture at sowing has the potential to increase the rain-fed wheat yield by 1.0–2.0 t/ha depending on actual conditions. Detailed studies are needed to quantify the effect of stored soil moisture on wheat yield in different climatic years. The estimated potential maize yield is similar to that of Wang and Han (1990). The estimated rain-fed maize yield is lower than that of Wang and Han (1990) in the northern parts of the plain. In this study, the estimated maize yields reflect the yield level that can be supported by water availability in the maize growing season from June to September if suitable maize genotypes can become available to fully utilize the resources in this period. Therefore, the estimated potential yields are expected to be higher than the yield levels of a specific cultivar that is currently in use because of the longer growing period assumed.

Since the late 1970s research has been carried out to investigate crop productivity in China (Huang, 1978). In the late 1980s extensive studies were conducted on quantifying the agro-climatic resources for cropping systems design in the NCP (Han, 1987; Han and Qu, 1987a,b). The NCP was considered to be one of the most productive agricultural areas in China due to the favourable temperature condition and abundant radiation resources. Since then, cropping systems have evolved into a dominant wheat/maize double cropping rotation. Assessment of the productivity of the wheat/maize system indicated that the region has high productivity potential, but it needs to be supported by irrigation to meet the crop water demand, especially for wheat (Wang and Han, 1990; Wang *et al*., 1992; Wu *et al*., 2006). The results of this study show that the water demand of the two crops cannot be fully met by extra water supply without depleting the groundwater resources. Compared with the current average maize yield (*ca* 7 t/ha), there may still be some potential to increase the yield of maize in some regions (Figure 7(b)). But for winter wheat, the yield level will be much lower in order to maintain a sustainable use of water resources. In areas north of 36 °N, wheat crop may need to be largely reduced or abandoned based on the average climatic conditions. Detailed studies are needed to assess whether dryland wheat or alternative crops can be profitable under the variable climate.

3.4. Impact of climate variability on crop water deficit and crop productivity in the NCP

Due to temporal and spatial climate variability, water deficit of wheat and maize crop varies both interannually and spatially (Figure 8(a), (b)). From 1961–2000, the estimated wheat crop water deficit at Fuyang ranges from −159 mm/year (159 excess) in wettest year to 234 mm/year in the driest year with an average of 106 mm. In contrast, at Beijing, this range becomes 197–569 mm/year with an average of 435 mm/year (Figure 8(a)). This implies that wheat crop water deficit in the wettest year at Beijing is even larger than that in the driest year at Fuyang. As a result, the estimated rain-fed wheat yield has a range of 2.8–7.0 t/ha (mean 4.6 t/ha) at Fuyang and 0–4.1 t/ha (mean 0.8 t/ha) at Beijing respectively (Figure 8(c)). At Nangong, Baoding, and Beijing, the estimated median wheat yield is zero, implying crop failure in more than 50% of the years if no irrigation water is applied. Due to the declining wheat yield with latitude under rain-fed conditions and its large interannual variability, detailed studies are needed to investigate which area in the NCP can have a profitable dryland wheat production system under the variable climate.

For summer maize, water deficit ranges from −402 to 322 mm/year (mean 44 mm/year) at Fuyang to −215–446 mm/year (mean 110 mm/year) at Beijing, respectively (Figure 8(b)). The maximum water deficit occurred at Nangong and reached 618 mm/year. Under rain-fed conditions, available rainfall can support maize grain yield level in a range of 3.4–13.6 t/ha (mean 8.9 t/ha) at Fuyang and 2.9–13.7 t/ha (mean 9.2 t/ha) at Beijing (Figure 8(d)). Although there can be crop failure at Nangong in extreme dry years, on average, the available rainfall can support a maize yield level of above 6 t/ha without irrigation in all areas of the NCP (Figure 7(b)).

The temporal and spatial variability of water deficit (Figure 8(a), (b)) leads to large interannual and spatial variability of wheat and maize yield under rain-fed conditions (Figure 8(c), (d)). This is in contrast to the crop yield under full irrigation (Figure 9(a), (b)). Under full irrigation, crop water demand is met, leading to much stable crop yield levels. Irrigation reduces most of the interannual and spatial variability in crop yield caused by climate variability (Figure 9(a), (b)). Abandoning or reducing irrigation will dramatically increase the spatio-temporal variability in crop yield (Figure 8(c), (d)). Under such situations, better management practices, such as opportunity cropping (what and when to crop depending on climate and soil conditions rather than a set annual cycle), better use of climate forecast information to direct decision making, are required to better manage the impact of interannual and spatial climate variability in order to achieve maximum return in good years while minimizing cost in bad years (see Hammer *et al*., 2000; McIntosh *et al*., 2005).

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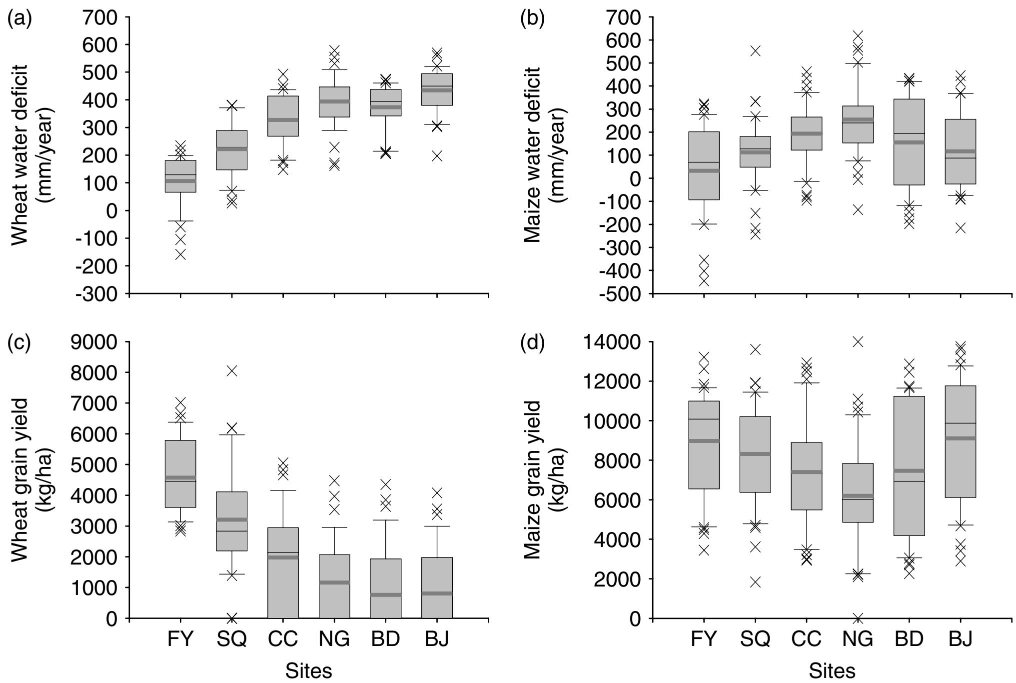

Figure 8. Changes of water deficit (a, b) and rain-fed grain yield (c, d) of wheat (a) and maize respectively with location/latitude (1961–2000). FY-Fuyang, SQ-Shangqiu, CC-Chaocheng, NG-Nangong, BD-Baoding, BJ-Beijing. Horizontal bars and upper and lower edges of boxes indicate 10, 25, 75, and 90 percentiles, thin black and thick grey lines in the box are the median and average respectively. The crosses indicate all the outliers. Impact of stored soil moisture at sowing time was not considered.

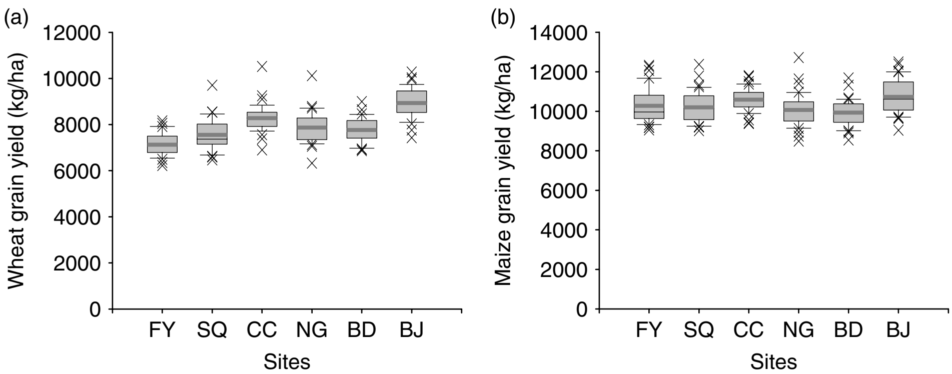

Figure 9. Changes of grain yield of wheat (a) and maize (b) under full irrigation with location/latitude (1961–2000). Horizontal bars and upper and lower edges of boxes indicate 10, 25, 75, and 90 percentiles, thin black and thick grey lines in the box are the median and average respectively. The crosses indicate all the outliers.

Several studies have shown significant climate trends from 1961–2000 in the NCP. These trends can be summarized as: significant decrease in global and direct radiation partially due to increase in aerosol loading (Yang *et al.*, 2004; Che *et al.*, 2005), increasing trend in temperature and atmospheric moisture content (Wang and Gaffen, 2001, Yang *et al.*, 2004), decreasing rainfall trend in northern part but increasing rainfall trend in southern part of the NCP (Yang *et al.*, 2004; Liu *et al.*, 2005), and a trend of declining PET (Thomas, 2000a,b; Gao *et al.*, 2006). To analyse the possible impact of these climate trends on agricultural water deficit, the yearly change of rainfall, PET derived from regression analysis and the difference between the two for the locations in this study are shown in Figure 10.

In general, Figure 10(a) shows a declining rainfall trend in the northern part, while showing an increasing rainfall trend in the southern part of the NCP. PET tends to have been decreasing in most parts of the plain, except in some areas of Shandong province and near Beijing and Ganyu where PET had an increasing or stable trend (Figure 10(b)). The difference between annual rainfall and annual PET had a decreasing trend in the northern part, but an increasing trend in the southern part of the plain, implying increased water deficit in the northern part, but reduced water deficit in the southern part in the last 40 years. This may have led to increased use of groundwater for irrigation in the north, while it increased rain-fed crop yield in the south. Detailed analysis indicates that the major changes in rainfall were during the

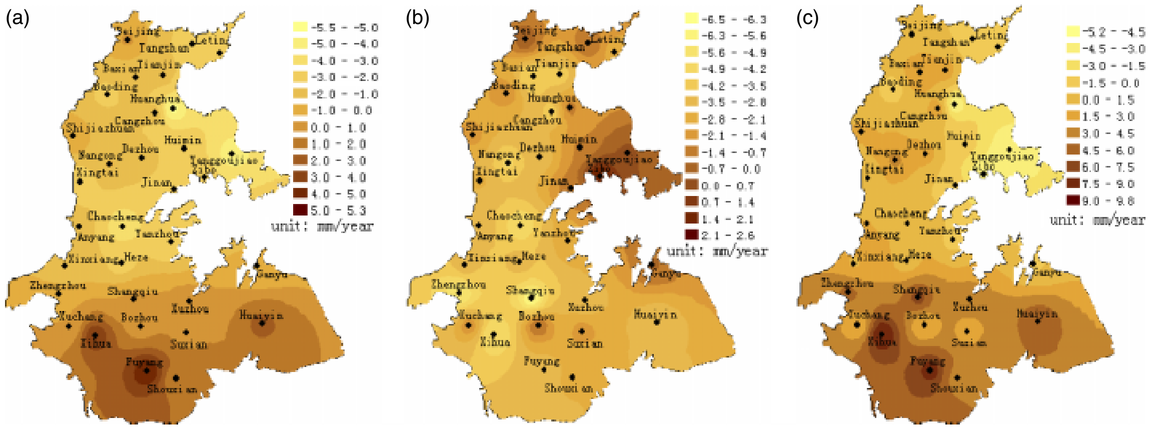

Figure 10. Annual changes (mm/year) of (a) rainfall, (b) potential evapotranspiration, (c) the difference between (a) and (b) in North China Plain (1961–2000). This figure is available in colour online at www.interscience.wiley.com/ijoc

summer rainfall period (data not shown). How much of this trend reflects long-term climate change or only a part of the climate variability remains to be further studied.

4. Conclusions

In the NCP, the monsoon climate with concentrated summer rainfall can support a high level of maize production in most parts of the plain. Use of groundwater for irrigation in the last 30 years has also led to high levels of wheat grain production, though rainfall in the wheat growing period is far less than wheat crop water demand, especially in the northern part of the plain. This has resulted in a dominant wheat/maize double cropping system with high productivity under irrigation.

The extensive use of groundwater for irrigation, together with the increased domestic and industrial water use, has caused rapid decline in the groundwater table, especially in areas north of the Yellow River, leading to hydrological imbalance and unsustainable future agricultural production. For long-term sustainability, use of groundwater in those areas has to be reduced or stopped in order to restore the hydrological balance.

It has been suggested that 'designing agriculture as a structural and functional mimic of natural ecosystems offered an integrated principle for working towards sustainable agriculture' (Hatton and Nulsen, 1999; Lefroy *et al*., 1999a,b). Based on this principle, the water use and water excess of a natural forest system, representing the natural system in the NCP, were estimated. The results show that the total water excess for surface flow and groundwater recharge under the natural vegetation would range from 21 mm/year in the north to 124 mm/year in the south. Such a system would use much less water than the irrigated wheat and maize crops together. In areas north of the 36°N line, the maize crop itself consumes as much water as the natural forest vegetation.

To maintain the water use of the natural system, wheat and maize crops would, on average, have a water deficit of 90–435 and 0–257 mm/year respectively. This implies that on average, all the areas north of the 36°N line (close to Anyang-Chaocheng line) have to abandon winter wheat due to its low grain yield. Further study is needed to assess whether dryland wheat or alternative crops are profitable in different climatic years. In most areas south of the 36°N line, rainfall is in excess of maize crop water demand, but not enough to support an added wheat crop. Only in the southernmost area can rainfall meet the water demand of two crops.

Due to the temporal and spatial variability of climate (especially rainfall), reducing or stopping irrigation will lead to a significantly lower wheat yield (0.8 t/ha in the north to 5.2 t/ha in the south on average) and increased variability in wheat and maize yield both interannually and spatially. Under such situations, better management practices, such as opportunity cropping, better use of climate forecast information to direct decision making, are required to better manage the impact of interannual and spatial climate variability in order to achieve maximum return in good years while minimizing cost in bad years.

Analysis on rainfall and PET from 1961 to 2000 shows that there has been an increasing trend in crop water deficit in the northern parts, but an decreasing trend in crop water deficit in the southern parts of the plain. This may have led to increased use of groundwater for irrigation in the north, while increased rain-fed crop yield in the south. Whether this trend reflects long-term climate change or largely as part of the climate variability remains to be further studied.

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List of Variables Used

D – annual deep drainage below the plant root zone (mm/year)

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DM – amount of biomass produced (kg/ha)
E – annual precipitation (mm/year)
E_0 – reference evapotranspiration as defined by FAO (Allen *et al*., 1998)
E_C – crop evapotranspiration (mm)
E_F – evapotranspiration of a natural forest system (mm/year)
E_{FM} – evapotranspiration of a natural forest system from June to September (maize season) (mm)
E_{FW} – evapotranspiration of a natural forest system from October to May (wheat season) (mm)
E_M – potential evapotranspiration in the Zhang *et al*. (2001) model, $E_M = 1400$ mm/year for forests.
E_S – evaporation from soil surface (mm)
H – crop harvest index–the ratio of harvest part to total above-ground biomass, 0.45 for wheat, and 0.5 for maize
K_C – whole season crop coefficient (−)
k – a crop-specific constant (kPa), $k = 55$ kPa for wheat, 90 kPa for maize
N – daily maximum duration of sunshine (hour)
n – daily actual duration of sunshine (hour)
P – annual precipitation (mm/year)
Q – annual water excess (runoff plus deep drainage) (mm/year)
Q_F – water excess of a natural forest system (mm/year)
R – annual runoff (mm/year)
R_a – daily extraterrestrial radiation (MJ/m^2/d)
R_s – daily solar radiation (MJ/m^2/d)
T_C – crop transpiration (mm)
w – fitted plant available water coefficient in the Zhang *et al*. (2001) model, $w = 2.0$ for forest
Δe – vapour pressure deficit (kPa)

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