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LETTER

Impacts of varying agricultural intensification on crop yield and groundwater resources: comparison of the North China Plain and US High Plains

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Supplementary material for this article is available online

Abstract

Agricultural intensification is often considered the primary approach to meet rising food demand. Here we compare impacts of intensive cultivation on crop yield in the North China Plain (NCP) with less intensive cultivation in the US High Plains (USHP) and associated effects on water resources using spatial datasets. Average crop yield during the past decade from intensive double cropping of wheat and corn in the NCP was only 15% higher than the yield from less intensive single cropping of corn in the USHP, although nitrogen fertilizer application and percent of cropland that was irrigated were both ~2 times greater in the NCP than in the USHP. Irrigation and fertilization in both regions have depleted groundwater storage and resulted in widespread groundwater nitrate contamination. The limited response to intensive management in the NCP is attributed in part to the two month shorter growing season for corn to accommodate winter wheat than that for corn in the USHP. Previous field and modeling studies of crop yield in the NCP highlight over application of N and water resulting in low nitrogen and water use efficiencies and indicate that cultivars, plant densities, soil fertility and other factors had a much greater impact on crop yields over the past few decades. The NCP–USHP comparison along with previous field and modeling studies underscores the need to weigh the yield returns from intensive management relative to the negative impacts on water resources. Future crop management should consider the many factors that contribute to yield along with optimal fertilization and irrigation to further increase crop yields while reducing adverse impacts on water resources.

1. Introduction

Food security is one of the largest concerns globally, particularly considering increasing global food demand related to projected population growth from 6.9 billion in 2010 to 10 billion in 2060 [1, 2]. In addition to rising population, increasing economic development has resulted in a shift towards more water intensive diets with rising meat and dairy demands [3]. Biofuel production is also increasing crop demands in many regions [4]. Crop production (mostly grain production) to meet rising food demands is projected to increase by a factor of ~2 from 2005 to 2050 [1]. Crop production can be increased by expanding cropland area (extensification) and/or by increasing crop yield (intensification, production/cropland area):

$$\text{Crop production} = \text{cropland area} \times \text{crop yield}. \quad (1)$$

The scope for increasing cropland area is mostly restricted to the tropics in S America, Central Africa, and SE Asia; however, expansion in those areas would adversely impact biodiversity and climate from release of carbon [5]. Therefore, the primary approach being

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considered to increasing crop production is through increasing crop yield [3]. Crop yields can be increased using many different approaches, including multi-cropping, inter-cropping, improved cultivars, increased use of irrigation, fertilization, pesticides, herbicides, increased plant density, soil fertility, and improved cultivars [3]. To identify areas with the most potential for increasing crop yields, recent research has focused on mapping the gap between actual and potential yields. Potential yield has been defined as the yield of adapted crop cultivars without any water, nutrient, pest, or disease limitations [6]. Potential yield often refers to irrigated yield in water limited regions; however, a water limited potential yield has also been defined referring to rainfed agriculture. Potential yield has been estimated from modeling, recorded highest yields in research stations, or maximum farmer yields from yield contests [7]. Yield gaps have been compared in similar climate zones globally to remove the impacts of climate variability on global yield gaps [8]. There is concern that crop yields have plateaued at ~80% of potential yield [7] and that it may be difficult to further increase crop yields in the future. Many studies emphasize the importance of increasing fertilization and irrigation to reduce yield gaps; however, they also underscore the need for doing this sustainably to reduce adverse environmental impacts [9, 10].

Major regions with yield gaps include the North China Plain (NCP, corn yield gap) and the US High Plains (USHP, wheat yield gap) based on global datasets [10]. In addition, adverse environmental impacts are widespread, with both regions considered global hotspots of groundwater depletion, which is the primary source of irrigation water [11–14]. The NCP is considered the grain basket of China accounting for 25% of wheat and 18% of corn production within the past decade (2002–2011). Food security is one of the most critical issues in China with ~20% of the global population (1.4 billion in 2010) [2] supported by only 8% of global arable land (2008) [15] and recently subjected to frequent droughts and floods [16]. However, China is the largest grain producer globally with increasing multi-cropping, fertilization (N, P, and K) from 1 kg ha^{-1} (1952) to 470 kg ha^{-1} (2011), irrigation from 14% (1952) to 38% (2011) of cropland, and improved cultivars [17].

Similar to the NCP in China, the USHP is also considered the grain basket of the US, with production accounting for 20% of wheat, 14% of corn, 29% of cotton, and 38% of sorghum within the past decade (2002–2011) [18]. Although food security is not as critical in the US as in China, with 4.5% of the global population (0.3 billion, 2010) [2] supported by 12% of global arable land [15], the US is the second largest grain producer globally, accounting for ~16% of global production in 2012) [2] and also the largest grain exporter globally, accounting for ~50 million tons of grain, 17% of the global export market [15]. Additional background information for the NCP and USHP is provided in supporting information (SI), section 1 (available at stacks.iop.org/ERL/10/044013/mmedia).

The objectives of this study were to:

- Compare impacts of multi-cropping and varying fertilization and irrigation intensities on crop yields in the NCP and USHP.
- Assess environmental impacts of variable agricultural intensities on water resources in both regions.
- Evaluate approaches towards more sustainable crop production in terms of water resources.

This study differs from many of the previous studies that have addressed yield gaps and sustainable intensification based on global analyses [8, 9] and instead focuses on comparison of varying agricultural intensification in the NCP and USHP relative to crop yields and water-resource impacts: double cropped intensively fertilized and irrigated corn and wheat in the NCP and single cropped, less fertilized and irrigated corn in the USHP (figure 1). Comparison of these large regional systems provides information on yield returns relative to agricultural intensification that is highly relevant at the global scale. The similarity in climate between the NCP and USHP removes the effects of climate from the intercomparison. This study also addresses spatiotemporal variability in yields and environmental impacts within the NCP and USHP. Both regions rely heavily on groundwater for irrigation [11]. The detailed comparison between the NCP and USHP allows us to evaluate approaches towards more sustainable management of agriculture in the future to reduce adverse impacts on water resources.

The paper includes a description of the regions and data analysis in the materials and methods section. The results and discussion section includes a general comparison of varying agricultural intensities related to yields in the two basins, followed by more detailed evaluation of spatial and temporal variability in yields in the two regions. The impacts on groundwater quantity and quality are then discussed. Yield gaps from global studies are compared with those based on this regional analysis. The many contributing factors to crop yield are described. Approaches towards more sustainable management are provided.

2. Materials and methods

Intensive versus extensive land management practices were compared by compiling spatiotemporal data on inputs, focusing on multi-cropping and fertilization and irrigation, relative to outputs, including crop yields, planted areas, and crop production for the NCP and USHP (figure 2). There are many similarities between the NCP and USHP, including suitable soils for

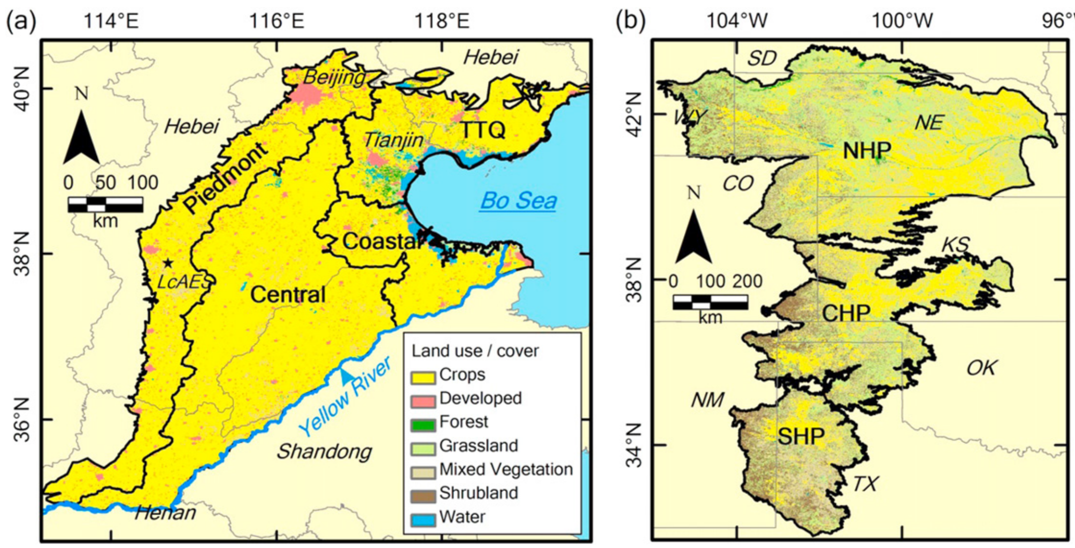

Figure 1. Land use/land cover in the (a) NCP and (b) USHP. Land cover maps are based on the ESA GlobCover Data in 2009 [70]. The NCP boundary in this study is based on the 100 m elevation contour line to the West and North, on the coastline of Bo Sea to the East and on the Yellow River to the South similar to the NCP outline used in many other studies [44]. The USHP boundary and subregions are based on those defined by the US Geological Survey for the Ogallala/High Plains aquifer boundary from the USGS (http://water.usgs.gov/GIS/dsdl/ds543.zip). The NCP includes parts of five provinces: Beijing (6500 km^2), Tianjin (11 300 km^2), Hebei (77300km^2), Shandong (31 400 km^2), and Henan (17 600 km^2). Sub-region boundaries of the NCP are based on geomorphologic and county boundaries and statistical data availability: Piedmont (~36 000 km^2): Piedmont plain of the Taihang and Yan Mountains, Central (~66 000 km^2): central plain, Coastal (~18000 km^2): coastal plain, and TTQ, parts of Tianjin, Tangshan and Qinhuangdao provinces (TTQ, ~24 000 km^2). The USHP includes parts of eight states: South Dakota (SD, 12 800 km^2), Wyoming (WY, 22 200 km^2), Nebraska (NE, 167,300 km^2), Colorado (CO, 34 500 km^2), Kansas (KS, 80,300 km^2), Oklahoma (OK, 19900 km^2), New Mexico (NM, 24500 km^2), and Texas (TX, 92 700 km^2), these states are located in the NHP (250 900 km^2), CHP(128 200 km^2) and SHP (75 100 km^2) which are defined by the US Geological Survey.

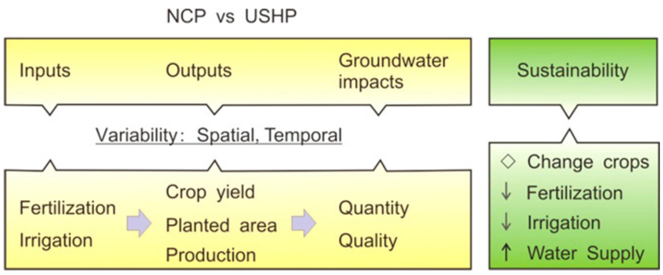

Figure 2. Schematic of methods used in the NCP–USHP comparison, including comparison of inputs (fertilization and irrigation), relative to outputs (crop yield, planted area, and crop production) in terms of impacts on groundwater quantity and quality. Spatial variability was evaluated considering data from 2002 to 2011 and temporal variability considering time trends from 1980 to 2011. Various approaches to increasing sustainability were considered.

cultivation with varying soil textures within each system (figure S1). Soil organic carbon (SOC) is important for fertility and levels are similar in the top meter of soil in both regions: NCP, 5.6 ± 0.4 kg SOC/m^2 USHP, 5.5 ± 1.6 kg SOC/m^2 [19]. Mean annual precipitation (NCP: 525 mm yr^{-1}; USHP: 517 mm yr^{-1}; 1980–2011) and air temperature (NCP: 13.1 °C; USHP: 11.4 °C; 1980–2011) are similar with most precipitation focused in the hot summer months (table 1; figure S2). Stream flow is negligible in both regions because of damming near the Taihang Mountains West of the NCP in the late 1950s to reduce flooding and to provide water for cities and because of low topography and internal drainage into ephemeral lakes or playas throughout most of the USHP (~66 000 playas) [20]. Only a few major rivers cross the USHP (e.g. the Platte and Republican rivers in the Northern High Plains). A major difference between the two regions is population density, with 117 million people in the NCP (818 people/km^2) and 2.9 million in the USHP (5.9 people/km^2) in 2011 (table 1, figure S3). Population density impacts farm size, with typical farm size of ~0.3 ha (4–5 mus) in the NCP versus ~500 ha in the USHP, generally resulting in less advanced technology for agriculture in the NCP relative to the USHP.

The analysis in this study focused on the dominant grain crops: wheat and corn in the NCP and USHP (figure S4). Evaluation of spatial variability included comparison of double cropping versus single cropping and average values of inputs and outputs between and

Table 1. Comparison between the North China Plain (NCP) and US High Plains (USHP).

	NCP	USHP
Area (1000 km^2)	144	450
% of country	1.5	4.8
Pop. (millions, 2011)	117	2.9
Pop. Dens.(people/km^2, 2011)	818	5.9
Prec. (mm, 1980–2011)	525	517
Temp. (°C, 1980–2011)	13.1	11.4
ET (mm, 1983–2006) [67]	484	432
Altitude (m)	0–100	590–2400 [68]
Dominant grain crops	Wheat, corn	Wheat, corn
Cropland (% of land)	54 (2005)	34 (2008)
Irrig. (% of cropland)	85 (2005)	42 (2005–2008)

Pop., population; Dens., density; Prec., precipitation; Temp., temperature; ET, evapotranspiration; Irrig., irrigated area.

within the NCP and USHP using data for the past decade (2002–2011). Analysis of temporal variability involved evaluation of long-term trends in inputs and outputs over the past three decades (1980–2011). Data on annual crop yields, planted areas, and crop production were compiled for each county in the NCP (219 counties) and USHP (233 counties) for 1980 through 2011. Information on data sources, including N and P (P_2O_5, the same bellow) fertilization and irrigation, is provided in SI, section 2 (available at stacks.iop.org/ERL/10/044013/mmedia).

Impacts of irrigation on groundwater depletion are recorded in different sources (SI, section 2 (available at stacks.iop.org/ERL/10/044013/mmedia)). In the NCP, contour maps of groundwater levels are available for 1959, 1984, 2001 [21]. Groundwater level monitoring data for 108 wells from 1990 through 2008 were obtained from China Institute of Geo-Environmental Monitoring (CIGEM) and 2010 data (69 wells) were obtained from the published yearbook on groundwater [22]. In the USHP, a groundwater depletion map for the USHP from predevelopment (year 1950 considered predevelopment) to 2011 based on 3322 monitored wells by various state agencies was obtained from the US Geological Survey [23].

Groundwater quality data are limited in the NCP but are much more detailed in the USHP. Only a small number of synoptic surveys have been conducted in different regions in the NCP, with maximal coverage of 200 wells in 1998–2000 [24]. Groundwater nitrate levels have been monitored in wells in the USHP from 1950 to 2010 (total 23 944 samples), which were used to assess spatial and temporal trends (SI, section 2 (available at stacks.iop.org/ERL/10/044013/mmedia)).

3. Results and discussion

3.1. Comparison of crop yield between the NCP and the USHP (2002–2011)

Intensive agricultural management in the NCP only marginally increased crop yield relative to less intensive management in the USHP. Double-cropping wheat and corn in the NCP contrasts with single-cropping corn in the USHP. Average annual crop production is similar in both regions, surprisingly; average yield from double-cropped corn plus wheat in the NCP (2002–2011) was only 15% higher than single-cropped corn in the USHP (figure 3, table 2, S1). In addition to the double cropping, the intensity of inputs (N and irrigation) was much greater in the NCP than in the USHP, with N fertilization on the wheat and corn rotation in the NCP being ~2 times that of corn in the USHP (table 2, figure 4). Percent of irrigated cropland in the NCP (85% of cropland, 2005) was also ~2 times greater than in the USHP (42%, 2005) (figure S5). Winter wheat in the NCP is grown during the dry season (16% of precipitation, October–following May) whereas summer corn in the USHP is in phase with the wet season (74% of precipitation, April–September). Because crop yields and planted areas are similar in the NCP and USHP, resultant (table 2).

The obvious differences between the two regions are the double cropping and intensity of fertilization and irrigation inputs. However, many other factors may contribute to crop yields, including cultivars, soil fertility, and planting density etc that will be discussed later. Higher corn yield in the USHP by almost a factor of 2 relative to that in the NCP may be explained in part by the effects of growing period length. Double cropping in the NCP restricts the corn growing season to 4 months, to accommodate winter wheat, relative to full season (6 month) corn in the USHP. The importance of growing period length to yield is supported by field studies in the NCP in 2013 that show that planting corn in the NCP ~30 days earlier increased yield by 30–40% (table S1). Additional evidence is provided by analysis of corn growth in the central US which shows that earlier planting dates in Nebraska (NHP) could account for 30–40% of the reported corn yield increase from 1979 to 2005; however, correlations are not statistically significant in Kansas (CHP) [25].

Much higher fertilization in the NCP relative to yields when both corn and wheat are considered together results in lower nitrogen use efficiencies (NUE) in the NCP relative to the USHP (table 2). However, wheat is more intensively managed in the NCP and corn in the USHP. Comparisons of fertilization versus yield for corn in the two regions are complicated by the differences in growing period length. Higher fertilization of wheat in the NCP relative to that in the USHP by a factor of ~3 is generally consistent with the ~3 fold higher wheat yield in the NCP relative to that in the USHP (table 2). Previous field experiments and modeling studies in Luancheng and Yucheng Agricultural Experiment Stations in the NCP indicate that total N application rates ⩾200–300 kg N/ha/yr for both crops (e.g. 400, 600, and 800 kg N/ha/yr) did not significantly increase wheat and corn yield, with highest NUE at 200 kg N/ha/yr total for both crops [26, 27]. In addition, field tests in Kansas in the USHP

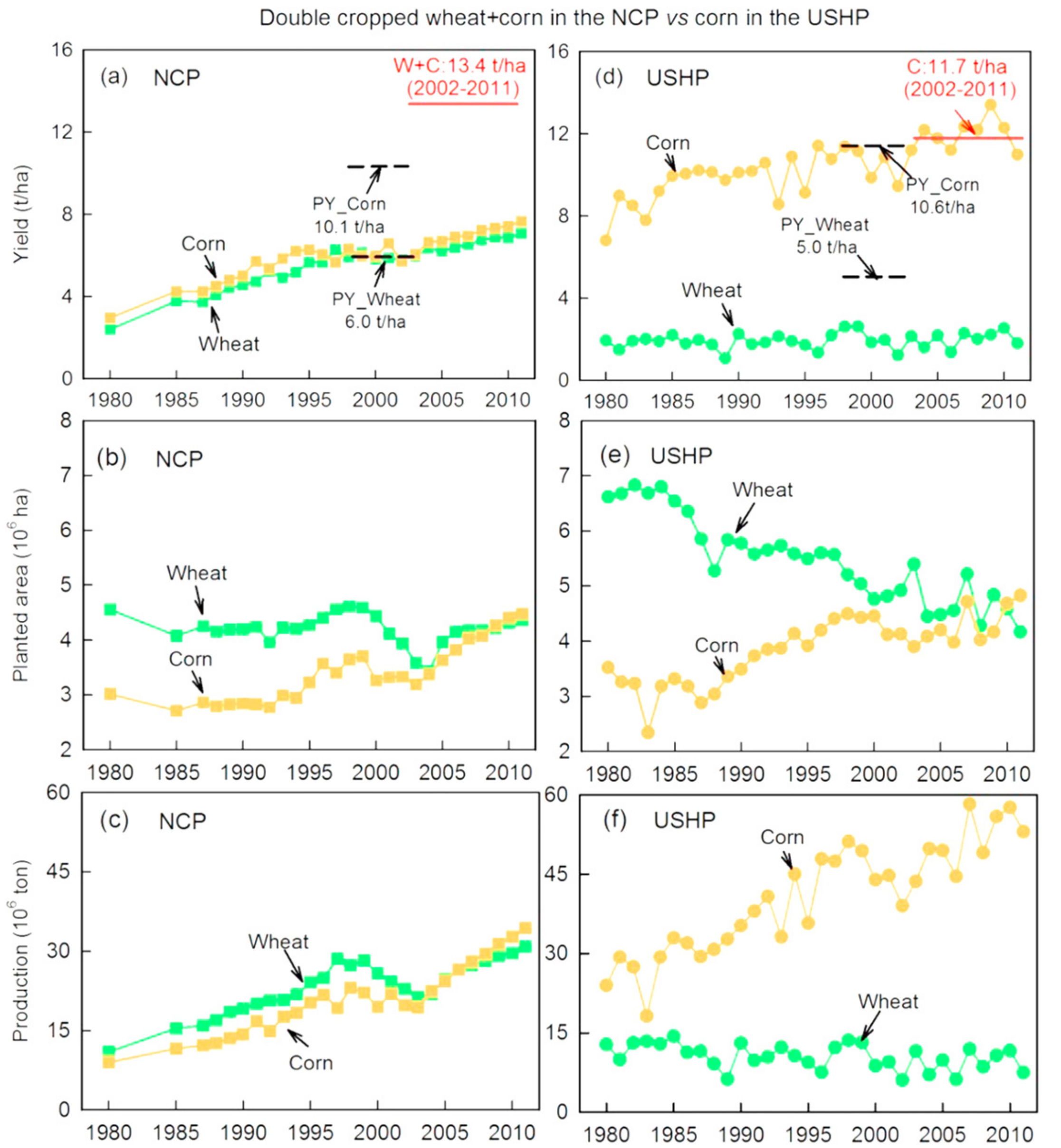

Figure 3. Variations in wheat and corn yield, planted area, and production in the NCP and the USHP (1980–2011). The wheat and corn (W + C) yield for the NCP is the annual yield of the typical double crop rotation, shown only for 2002–2011 because of differences in planted areas for corn and wheat prior to that, making it difficult to calculate average yields. The source of the data is provided in SI, section 2 (available at stacks.iop.org/ERL/10/044013/mmedia). Double cropped wheat and corn in the NCP accounted for 98% of total grain production, 48% wheat and 50% corn(2002–2011). Double cropping is dominant in the Piedmont and most of the central parts of the NCP, with a mean Multiple Crop Index (MCI) of ~1.6, which indicates the number of times the crops are sown per year (Beijing, Hebei, Henan, Shandong, Tianjin statistical yearbooks, 2008). The mean wheat +corn yield in the NCP during the past decade (2002–2011: 13.4 t/ha, dashed red line in subfigure-(a)) is 15% higher than the mean corn yield in the USHP (11.7 t/ha, dashed line in subfigure-(d)) during 2002–2011. The wheat yield in the NCP and the corn yield in the USHP already exceed potential yield (PY) calculated from a global dataset as a single crop system [10], however, corn yield in the NCP and wheat yield in the USHP have yield gaps relative to global data. Single cropped corn in the USHP accounts for 78% of total grain production (2002–2011). Single annual cropping is dominant in the USHP, all corn data used in this research is corn for grain, corn planted area for silage in the USHP is ~ 0.1 mha versus 3.8 million ha for grain, and most is in the NHP (81%) (1980–2011) [18].

indicate that the optimum N fertilizer input for maximum corn yield was ~200 kg N/ha [28, 29]. Application of the RZWQM2 model to simulate both wheat and corn yield data in the NCP from 1970 to 2009 at 15 sites indicates that fertilizer application rates could be reduced by 40–60% and irrigation by 60–80% relative to current rates without compromising crop yield [30]. For example, the analysis indicated that N application rates at Luancheng station could be reduced from 550 to 210 kg N/ha/yr [30]. It is possible that the high intensity of irrigation and fertilization are working against each other in the NCP, with intensive irrigation leaching fertilizers before plant uptake.

3.2. Comparison of global versus regional analysis of yield gaps

Global analysis of crop yield gaps indicates that mean and maximum yield gaps were ⩽20% for wheat in the

Table 2. Summary of wheat and corn data for 2002–2011 in the NCP and USHP.

	W–Y, t/ha	C–Y, t/ha	W–PA, mha	C–PA, mha	W–Pr, mton	C–Pr, mton	W–N, kg ha^{-1}	C–N, kg ha^{-1}	W–NUE[a]	C–NUE	IRRIG-Crop	GWLD, m yr^{-1}
NCP	6.5	6.9	4.0	3.9	26.2	26.8	202	127	32	54	85%	0.57
USHP	1.9	11.7	4.7	4.3	9.1	50.0	74[b]	155[c]	36	74	42%	0.48

[a] NUE is get from crop yield divided by crop fertilizer application, similar method as Tilman *et al* [69].

[b] Wheat N application in Kansas;

[c] Corn N application is only available by state and data for Nebraska are selected in the table, corn N application in Kansas is 159 kg N/ha and in Texas is 158 kg N/ha, while wheat N in Nebraska is 61 kg N/ha and in Texas is 75 kg N/ha (2002–2011).

W–Y: wheat yield; C–Y: corn yield; W–PA: wheat planted area; C–PA: corn planted area; W–Pr: wheat production; C–Pr: corn production; W–N: nitrogen fertilizer application for wheat; C–N: nitrogen fertilizer application for corn; IRRIG-Crop: irrigated percentage of all cropland (NCP in 2005, USHP in 2005–2008); GWLD: average groundwater level decline.

Units: t, metric ton; ha, hectare; mha, million hectares; mton, million metric tons. Data on irrigated and rainfed corn in the USHP are incomplete (74%–88% reporting, 2002–2011) by the National Agricultural Statistics Service, US Dept. of Agriculture. Data in this table refer to average values for irrigated and rainfed crops throughout the NCP and USHP. Because crop yields and planted areas for C + W in the NCP are similar to those for corn in the USHP, crop production is similar in both regions NCP: 53 million tons (mtons) of corn plus wheat; USHP: 50 mtons of corn. N fertilization on the wheat and corn rotation in the NCP (329 kg ha^{-1}) is ~2 times that the corn in the USHP (155 kg ha^{-1}, Nebraska). More detailed data, including information for subregions of NCP (Piedmont, central, and coastal plains and TTQ municipalities) and USHP (NHP, mostly Nebraska; CHP, mostly Kansas; and SHP, mostly Texas), are provided in SI section 2 and table S1 (available at stacks.iop.org/ERL/10/044013/mmedia).

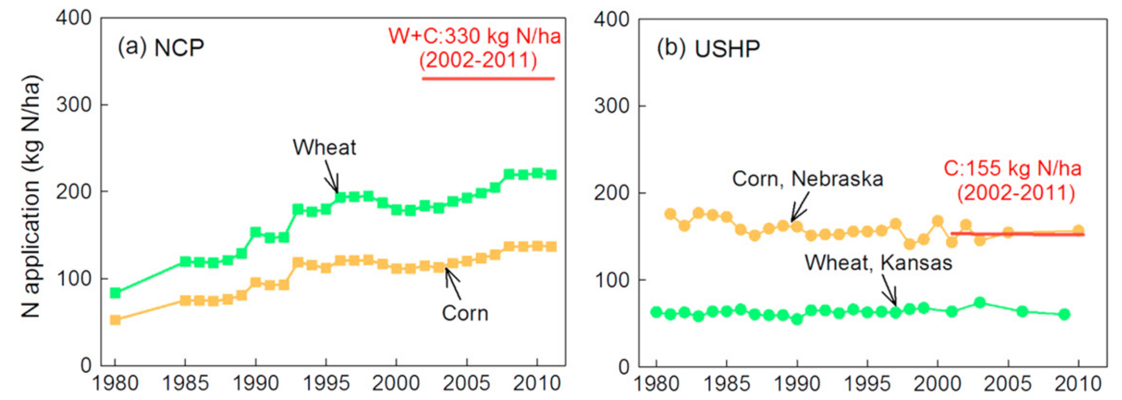

Figure 4. N fertilizer application rate for wheat and corn in the (a) NCP (1980–2011) and (b) USHP (1980–2012). Average N application for the doubled cropped wheat and corn is shown for the past decade (2002—2011) when the planted areas for the two crops are similar. The source of the data is provided in SI, sections 2, 1–2 (available at stacks.iop.org/ERL/10/044013/mmedia). Fertilizer application refers to N or P application/ha of crop planted area.

NCP and corn in the USHP but were about 50% for corn in the NCP and 50% for wheat in the USHP [8] (table S2). These yield gaps were identified by comparing actual yields with 90th percentile yields from regions in similar climate zones.

The ~50% yield gap for corn in the NCP identified from global modeling [8] is consistent with the 40% lower corn yield in the NCP relative to that in the USHP (table S2). However, the potential corn yield in the NCP from the global analysis most likely does not consider the double cropping in the NCP which restricts the growing season to 4 months to allow for winter wheat, relative to the ~6 month growing season in the USHP. The importance of planting dates and maturity ratings in defining potential crop yield was emphasized in previous analyses [7] and is pertinent in the case of the apparent corn yield gap in the NCP. A more detailed modeling analysis for the NCP for corn indicates that the potential yield has been declining during the past few decades (1981–2009) because of increasing temperature and decreasing radiation whereas actual yield has been increasing, attributed primarily to improved cultivars and increasing planting density [31]. This study indicates that the potential yield has been reached at the Luancheng station in the Piedmont. Similar research on wheat also showed that the wheat yield gap was stagnating in about a third of the wheat area and the yield gap has decreased regionally [32].

There is substantial variability in potential yields in the USHP. For example, irrigated corn potential yield in Nebraska based on farmers yield contests sanctioned by the US National Corn Growers Association (NCGA) is ~18.6 t/ha (1988–2013; figure S6). This potential yield is ~60% higher than the climatic potential yield identified for Nebraska (11.5 t/ha) from the global analysis [8]. Current yield for irrigated corn in Nebraska (2002–2011; 11.3 t/ha) is ~100% of the estimated potential yield from the global analysis [8] and ~60% of the NCGA potential corn yield (figure S6). Comparison of actual and simulated corn yields in Nebraska indicates that irrigated corn yields averaged about 80% of potential yield [7]. This analysis emphasized the impacts of seasonal weather uncertainties in yield gaps.

The ~50% yield gap for wheat in the USHP based on the global analysis is similar to the estimates of the yield gap (~55–60%) based on actual yields in Central High Plains (CHP) and SHP of up to 3 t/ha and statistical maximum yields of 6.6 t/ha for rainfed wheat and 7.7 t/ha for irrigated wheat [33]. While some of the yield gap may be related to livestock grazing of wheat rather than harvesting grain, this was difficult to quantify [33, 34]. Analysis in this study indicates that mean N fertilization of wheat ranges from 39 to 47% of that for corn (1980–2011; table S3, USDA 2013) and irrigation of wheat is also less than that of corn; however, there is limited data on irrigation for wheat. Less intensive management of wheat versus corn in the USHP may reflect economic factors also.

3.3. Spatial variability in crop yield relative to irrigation and fertilization within the NCP and USHP (2002–2011)

It is important to evaluate spatial variability in yields within the NCP and USHP to assess the representativeness of the average values discussed in the previous section. Spatial variability in crop yields within the NCP and USHP is not very high and spatial variations in crop production generally reflect differences in planted areas within the NCP and the USHP.

Within the NCP, wheat and corn yields are fairly uniform spatially, varying $\leqslant \pm 20\%$ from the mean across the different regions of the NCP, slightly higher in the Piedmont and lowest in the coastal region (table S4). Most (~85%) cropland is irrigated (2005) (table 1). N is the dominant fertilizer (59% of total fertilizer application), followed by P as P_2O_5 (27%) and K as K_2O (14%) in the NCP (2002–2011; table S5), N applied to wheat is ~1.5 times greater than that applied

Table 3. Fertilizer application, grain production trends and impacts on groundwater in the NCP and the USHP (1980–2011).

		NCP			USHP		
		1980	2011	Change	1980	2011	Change, %
	Wheat	3.2	7.2	125%	1.8	2.0	11%
Yield (t/ha)	Corn	3.7	7.6	105%	8.5	12.3	45%
	Wheat	4.3	4.2	−2%	6.7	4.3	−36%
Planted area (mha)	Corn	2.4	4.2	75%	3	4.7	57%
	Wheat	14.0	30.0	114%	12.2	8.9	−27%
Production (mton)	Corn	7.2	30.6	325%	25.1	56.1	124%
	Wheat	104	227	117%	61[a]	66	9%
N Fertilizer (kg N/ha)	Corn	67	142	113%	162[a]	151	−7%
Water Level, change (m yr^{-1})		8.88[b]	13.75[b]	−0.29	31.1	34.1	−0.1

[a] Corn N fertilizer in the USHP is from Nebraska and wheat N fertilizer is from Kansas.

[b] Data for 1993, [b] data for 2010. Values for 1980 and 2011 were estimated using linear regression based on long-term data for both the NCP and the USHP. More detailed information on long-term trends is provided in SI, table S5.

to corn (table 2), but residual soil N from wheat should be available for corn as a result of the double cropping. Previous studies indicate that manure applications are limited, ranging from ~5% to 20% of fertilizer N applied to wheat and corn, respectively [36], similar to results in this study (table S6). Production of wheat and corn is highest in the central plains (45% of the NCP production) and lowest in the coastal plain (9% of the NCP production), primarily resulting from spatial variability in planted areas (table S4).

In the USHP, corn yield is also fairly uniform across the different subregions, varying ⩽ ± 15% from the mean in the NHP, CHP, and Southern High Plains (SHP) (table S4). For corn in the USHP, N represents 68% of total fertilizer application while N for wheat is 50% of total fertilizer application (2002–2011; table S5). N fertilizer applied on corn is ~2 times greater than that applied on wheat (table S3), and most corn is irrigated, 70% in the NHP (2007), 74% in the CHP (2007), and 96% in the SHP (2010). Irrigated corn yield is ~2–3 times greater than rainfed yield (e.g. 10.7 versus 5.0 t/ha for the NHP, 10.0 versus 3.2 t/ha for the CHP, table S4). Because irrigated corn yields are generally similar across the regions in the USHP, variations in corn production mostly reflect differences in planted areas, highest in the NHP (~79% of production and 79% of planted area), followed by the CHP (~19% of production and of planted area) and the SHP (~2% of production and of planted area) (table S4).

Average wheat yield is only 16% of corn yield in the USHP, highest in the NHP (20%), decreasing through the CHP (16%) and lowest in the SHP (8%) (table 2 and S1). Irrigation is much lower for wheat than for corn, 53% of wheat production in CHP, followed by 41% in NHP, and only 6% in the SHP. Yield from irrigated wheat is almost double that of rainfed wheat (table S4). The planted area of wheat is highest in the CHP, followed by the NHP, and SHP, resulting in highest average annual wheat production in the CHP (53%), related mostly to higher planted area, followed by the NHP (41%) and the SHP (6%) (table S4).

3.4. Temporal variability in crop yield (1980–2011)

Temporal variability in yield, planted areas, and production over the past three decades provides an understanding of the evolution of crop management over time. In the NCP, wheat and corn yields about doubled (125% and 105%) from 1980 through 2011 (table 3 and S5, figure 3(a)). Wheat planted area remained relatively stable over time (4.3–4.2 mha, figure 3(b)); therefore, approximate doubling of wheat yield (125%) resulted in similar doubling of production (114%) (equation (1)). Corn planted area was ~65% of wheat planted area in 1980 but increased to slightly exceed wheat planted area in 2011 (75% increase, figure 3(b)); therefore, approximate doubling of yield and planted area resulted in approximate quadrupling of corn production (325%) (table 3 and S7, figure 3(c)). Temporal trends in crop yield are highly correlated with N and P application rates ($r^2 = 0.94$ and 0.97, figures 5 and S6). N application (wheat and corn) about doubled in the NCP while P application (wheat and corn) increased about six fold from 1980 through 2011 (figure S7). Low P levels in the 1980s (~25 kg ha^{-1} for wheat and 40 kg ha^{-1}) relative to those applied in previous field studies (52 kg ha^{-1} for wheat and 90 kg ha^{-1}) [35] suggest that P may have originally been limiting. However, P levels in the past decade (48 kg ha^{-1} for corn, 75 kg ha^{-1} for wheat, 2002–2011) are similar to those applied in previous field experiments 52 kg ha^{-1} for corn, 90 kg ha^{-1} for wheat, 1990–2006), indicating that P should no longer be a limiting nutrient [35]. The large increases in P application rates may have contributed to the yield increases in the NCP (figure S7). While there is a strong correlation between yield and fertilizer inputs, field and process modeling studies indicate that the statistical relationship between grain yield and N

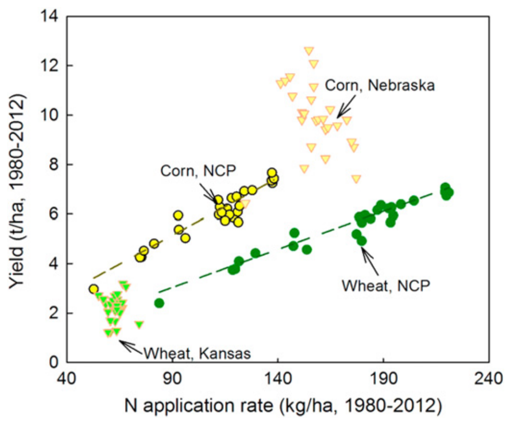

Figure 5. Correlations between wheat and corn yields with N application in the NCP (1980–2011) and corn yield with N application in Nebraska and wheat yield in Kansas, the USHP (1980–2012). Data for the NCP are based on the statistical yearbooks and for the USHP on the USDA dataset [71]. Note large increase in corn yield in Nebraska with little additional fertilizer. It is difficult to estimate true fertilizer input for double cropping systems because residual N from one crop should be available for the next crop, e.g. higher N application for wheat likely contributes indirectly to corn yield in the NCP.

application over the past three decades in the NCP (figure 5) may not be entirely causal and that other factors may contribute to increased grain yield [26, 27]. Data on temporal variability in irrigated areas or irrigation applications are limited; however, simulated irrigation and related groundwater level declines showed lowest declines in the 1970s and increasing declines with time with the most rapid declines in the mid-1990s through early 2000s (figure S8(a)).

In the USHP, increases in corn yield (45%, table 3, 1980–2011) were about half of the NCP corn plus wheat yields (111%, 1980–2011) (figures 3(a) and (d), table S7). Corn planted area also increased by a similar amount (57%) to yield (45%), resulting in about doubling of corn production (124%, 25.1–56.1 million tons, mtons). Increases in corn yield were greatest in the NHP (51%) followed by the CHP (27%) and decreases in the SHP (−11%) whereas increases in corn planted areas were greatest in the CHP (150%) followed by the NHP (44%) and stable in SHP (0%). Resultant increases in corn production were greatest in the CHP (231%), followed by the NHP (115%), and decreases in SHP (−36%). Corn yield increases were greater in rainfed versus irrigated cropland (218% versus 81% in NHP and 71% versus 57% in the CHP). Increases in corn yield cannot be explained by increased fertilization, which remained fairly stable over time (figures 4 and 5). There was no systematic variation in irrigation pumpage since peak pumpage in the mid-1970s (figure S8(b)). Most of the increase in irrigation (~420%) occurred prior to 1980 (~1950–mid 1970s) but groundwater depletion continued (figure S8(b)). Wheat yield increased slightly over time by 11% (1980–2011), ranging from 19% increase (both rainfed and irrigated) in the NHP to 27% reduction in the SHP (table S7). Wheat planted area decreased by 36% over this time, generally evenly distributed across the three regions of the USHP; the resultant wheat production decreased by 27% across the USHP.

In the NCP, wheat and corn yields are not correlated with precipitation ($r^2 = -0.002$) or within each sub-region because irrigation essentially eliminates the natural water limitation in this semiarid region. In the USHP, interannual variability in corn yield was much less for irrigated versus rainfed corn in the NHP and CHP, showing that irrigation essentially decouples corn yield from precipitation variability (figure S9). Irrigation greatly reduces drought vulnerability of corn yield: mean irrigated corn yield was similar to the long-term mean yield (1980–2011) during recent drought years in the NHP (2002 and 2011 droughts, figure S10, 0–4% higher mean corn yield relative to long-term mean in NHP and CHP). In contrast, rainfed corn yield in the NHP decreased by 63% in 2002 and in the CHP decreased by 65% in 2002 and 56% in 2011 because of serious droughts. Therefore, droughts resulted in marked differences in yield between irrigated and rainfed corn (~540% in NHP in 2002 and ~770% and 600% in CHP in 2002 and 2011). The distribution of the droughts is shown in figure S9 for 2002 and 2011 in the USHP [37].

3.5. Factors impacting grain yields

Many factors can impact grain yield beyond the focus on double cropping and related crop growing period, fertilization, and irrigation discussed in this study. Additional contributing factors include weather and climate, plant density, soil fertility, and cultivars related to crop breeding. A reconnaissance evaluation reveals the relative importance of some factors. Irrigation has essentially decoupled crop yield from precipitation variability in many of these regions. Modeling analysis shows that wheat yield in the NCP is positively correlated with daily sunshine hours and diurnal T range (daily $T_{\max} - T_{\min}$) and negatively correlated with relative humidity. Simulation results show declining trends in winter wheat with reductions in daily sunshine hours and diurnal T range; however, these changes were compensated by increases in actual yield related to other factors [38]. Modeling studies have also isolated planting density as an important contributor to increasing grain yield in the NCP [31]. Incorporation of straw mulch into soils has increased soil organic matter since the 1990s in the NCP by ~50% [39] and SOC under no tillage was ~33% higher than that under conservation tillage in parts of the CHP, USHP (1982–2002) [40]. Varying crop cultivars may also be linked to impacts of extended growing season and plant density effects on yield. Increases in wheat yield in the 1990s and 2000s relative to the 1980s were attributed primarily to improvements in crop cultivars (25% yield increase in 1990s and 52% in 2000s than in the 1980s) relative to fertilization and soil fertility (both ~7% yield increase in 1990s and 2000s) based on long-term field experiments at Luancheng station (1979–2012) and modeling analysis using the CERES–Wheat model [38]. Field experiments (1980–2009) at four stations in the NCP and crop modeling also showed that cultivars contributed 12–23% of absolute wheat yield increase relative to 2–4% from fertilization management [41]. Dwarfing genes in wheat and other genetic improvements contributed substantially to yield increases [42, 43]. These studies show the large number of factors that can impact crop yield and the difficulties of attributing yield increases to specific factors. Many of the factors contributing to increased yield are linked and are not mutually exclusive; however, several studies emphasize the importance of improved cultivars and crop breeding linked to other factors in increasing crop yields.

3.6. Impacts of agricultural production on groundwater quantity

Throughout the NCP, groundwater resources were depleted by 92.8 km^3 (~20 mm yr^{-1}, 1980–2011, table S8) based on groundwater level monitoring and modeling analyses [41]. Simulated groundwater depletion is highest in the Piedmont (45 mm yr^{-1}), lower in the central (16 mm yr^{-1}), and lowest in the coastal (4 mm yr^{-1}) and TTQ (5 mm yr^{-1}) regions (table S8, figure 6(a)), similar to the spatial distribution in irrigated areas (figure S5(a)). The water table in 2010 was deepest in the Piedmont (23.5 m), followed by the central (13.2 m), TTQ (7.4 m) and coastal (4.7 m) regions (figure S11(a)). Depth to groundwater is greatest in the region around Luancheng station in the Piedmont, where it declined from ~10 m in 1978 to 42 m in 2013 (~1 m yr^{-1}) based on monitoring in Luancheng station (table S9, figures 6(a) site (b)).

Groundwater depletion in the USHP totaled 176 km^3 (12 mm yr^{-1}, 1980–2011, table S8). Groundwater depletion is lowest in the NHP (3 mm yr^{-1}, 1980–2011) (table S8, figure 6(b)), attributed to higher groundwater recharge (51 mm yr^{-1}, Nebraska) [45] and use of surface water to supply ~24% of irrigation water [46]. Greater depletion in the CHP (21 mm yr^{-1}) and SHP (27 mm yr^{-1}) is attributed to much lower recharge in these regions (~10 mm yr^{-1}) [45]. Depletion exceeds recharge by up to a factor of 10 in some parts of the CHP and SHP [47]. The average water table in 2011 is deepest in the CHP (~50 m), followed by the SHP (~45 m), and the NHP (~23 m) (figure S11(b)), depths to the groundwater table in some sites are ~100 m (table S9, figure 6(b) site (B) and (E)). The remaining aquifer saturated thickness [48] ranges from an average 250 m in the NHP, 100 m in the CHP, and 52 m in the SHP (figure S12). The remaining saturated thickness is ⩽10 m in 24% of the USHP, mostly in the CHP (10%), followed by the NHP (8%) and the SHP (6%) (figure S12). Projected depletion in some places is up to ~40% of the groundwater storage in parts of the CHP in Kansas over the next 50 yr while ~30% has been depleted to date [49].

Comparing depletion over similar time periods in the NCP and USHP (1980–2011) shows that depletion in the NCP (~90 km^3) is about half of that in the USHP (176 km^3) although the irrigated cropland area is similar in both regions (2005: NCP, 6.6 mha; USHP, 7.2 mha). The difference in depletion is attributed to higher recharge in the NCP (~120 mm yr^{-1}) [44] relative to that in the USHP (~26 mm yr^{-1}) [45]. In addition, the Taihang and Yan mountains (186 000 km^2) to the West and North contribute flow to the NCP whereas the USHP is mostly isolated from surrounding regions.

3.7. Impacts of agricultural production on groundwater quality

In the NCP, limited groundwater quality data preclude detailed evaluation of agricultural impacts. The most comprehensive evaluation includes 295 samples (1998–2000) which showed that 13% (38 out of 295) of wells exceeded the US EPA maximum contaminant level (MCL) of 10 mg NO_3–N/L, highest in the Piedmont (26 out of 61 samples) [24]. Unsaturated zone sampling coupled with crop yield and fertilizer data indicate nitrate accumulation in deep soils and high potential for nitrate leaching, particularly during the summer corn season in response to intense rains [26]. Limited data (36 samples) from a survey in the lower coastal plain showed that NO_3–N in shallow groundwater averaged 24.1 mg NO_3–N/L, 60% (22 of 36) of samples exceeding the MCL [50]. A synoptic survey (27 samples) in the Southern region reveals that groundwater nitrate was related to field fertilization, irrigation, and water level depth in a shallow groundwater region adjacent to the Yellow River [51].

In the USHP, impacts of agriculture on groundwater quality are essentially inversely related to those on groundwater quantity [52–54]. Nitrate contamination (figure S13) is greatest in regions with little groundwater depletion because depth to the water table is shallowest (figure S11(b)), recharge is highest [45], soil clay content is low (figure S1(b)), resulting in leaching more nitrate to the underlying aquifer (figure S13) [55]. NO_3–N concentration in the groundwater was very low before 1970 and increased from the 1970s to the 1990s, then became stable within the late decade (figure S14). Highest groundwater nitrate contamination (mean = 7.6 mg N/L, 81% of ~25 000 wells, 1980–2013) is found in the NHP where long-term depletion is lowest and recharge is highest. In contrast, groundwater nitrate contamination is lowest (mean = 1.5 mg N/L, 13% of ~25 000 wells, 1980–2013) in the CHP where groundwater depletion is high and recharge is low associated with more fine-

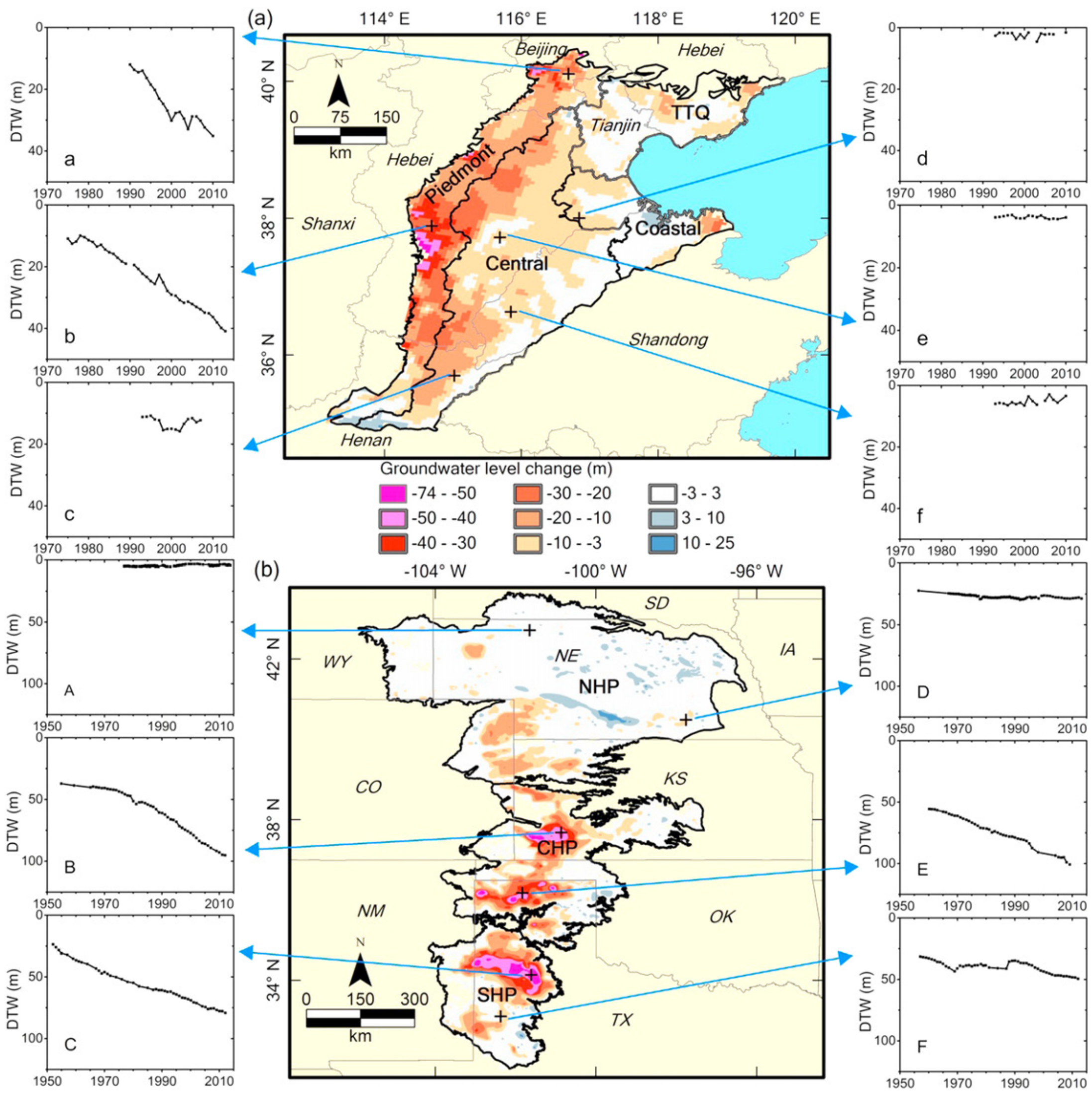

Figure 6. Groundwater level change (GWLC) with representative hydrographs showing changes in depth to water table (DTW) during the rapid agricultural development period in the (a) NCP (1970–2008) and the (b) USHP (1950–2011). Spatial resolution for the NCP map is 5 × 5 km and for the USHP map is 0.5 × 0.5 km. Sources of data for groundwater depletion in the NCP [21, 44, 72] and for the USHP [23]. Groundwater level hydrographs for the NCP are based on [44] using the China Institute of Geo-Environmental Monitoring (CIGEM) dataset (1990–2008) and extending it to 2010 using data from the published yearbook [22].

grained soils (figure S1(b)). Nitrate contamination is also high (mean = 5.2, 6% of ~25 000 wells, 1980–2013) in the Southern part of the SHP because soils are sandy and recharge is moderately high (figure S1(b)) [53]. Groundwater nitrate exceeds the MCL in 16% of 4090 wells in the USHP, 21% of 2947 wells in the NHP, 1% of 999 wells in the CHP and 22% of 144 wells in the SHP (2006–2010) (table S10).

3.8. Approaches towards more sustainable agricultural management

Comparisons of crop production and environmental impacts between the NCP and USHP should help us move towards more sustainable agricultural management, maintaining or increasing crop yield while reducing adverse environmental impacts, especially for the NCP. Three basic approaches are considered: (1) changing crop rotations, (2) reducing water and fertilizer applications, and (3) increasing water supplies; however, these approaches are not mutually exclusive.

(1) The NCP–USHP comparison suggests that *switching crop rotations* from double cropping wheat and corn to single cropping corn with an extended growing season in the NCP might achieve almost similar yields and would reduce irrigation demand by omitting 2–3 irrigation applications during the winter wheat season (~120–180 mm, ~50% of annual application) and also fertilizer applications. Therefore, converting double cropped area to single crops or three crops in two years may optimize the tradeoff between yield and adverse environmental costs by reducing irrigation [56] and fertilization with minimal reduction in crop

yield and significant advantages to water resources. An estimated 30–40% yield increases associated with 30 day extension of the corn growing season based on recent research in the NCP (table S1) is consistent with earlier planting dates resulting in 30–40% of the past yield increases in the Northern part of the USHP, Nebraska [25] and also similar increases in nearby Wisconsin [57].

(2) *Reducing water applications* by switching from irrigated to rainfed wheat would reduce yield by a factor of ~2 in both the NCP [58] and in the CHP and SHP of the USHP [59], but would greatly increase interannual variability and drought vulnerability of crop production as shown in the USHP in this analysis (figure S9). Increasing irrigation efficiency should reduce leaching of nitrate to underlying aquifers; however, there is controversy about the net benefit of increased irrigation efficiency at larger spatial scales in terms of water quantity. Switching from flood to sprinkler irrigation in the NCP may not increase net water savings because irrigation return flow recharges underlying aquifers [60]. In addition, large center pivot sprinkler technologies (~50 ha) became much more popular in the USHP in the 1980s (table S11), but this technology cannot be applied in the NCP because of the much smaller farm size (typically 0.3 ha). Many studies suggest using subsurface drip irrigation to better match water and nutrient demands with supplies from irrigation [28]. There is also a limit to irrigation efficiency because of salt build up in the central and coastal parts of the NCP and in parts of the CHP and SHP in Texas [61]. A certain amount of excess irrigation water is required to flush salts through the soil zone. Variability in crop yield and environmental risks should increase with climate extremes [62], such as increased irrigation water requirements associated with increased potential evapotranspiration in extreme dry years, and also nitrate leaching to underlying aquifers after intense precipitation.

Sustainability relative to *groundwater quality* could be enhanced by reducing fertilizer application and matching nutrient demand with supply both spatially and temporally. Reducing N leaching is a critical issue which affects water resources in the NCP and in the USHP, particularly in the US NHP [63]. The amount and timing of fertilizer application needs to be optimized to coincide with crop demand and minimize runoff or leakage, and there has technological disadvantage of the NCP compared with the USHP. This synchronization could be achieved using subsurface drip irrigation. Even though many best management practices have been applied in Nebraska to reduce groundwater nitrate contamination [64], nitrate contamination trends have only been reversed in 2 out of 17 management areas showing the difficulties of reversing long-term trends [63]. Socioeconomic factors also need to be considered. Many farmers in China are part time and also work in nearby cities to increase their income several fold; therefore, they have limited time for farming and are unwilling to risk applying less nitrogen to their crops and are insensitive to fertilizer costs [65].

(3) *Increasing water supplies* is difficult because irrigated agriculture cannot generally support expensive technologies, such as desalination of brackish water. However, increasing water supplies to meet municipal demand in the NCP could reduce water demand in general and increase water availability for irrigated agriculture. Transporting water from outside of the NCP through the South to North Water Transfer central route from the Yangtze River basin in the humid Southern region should free up water previously used by cities from large reservoirs to the West near the Taihang Mountains (table S12). This resultant increased water availability could then be used to replenish the aquifer in the Piedmont, either through irrigation return flow from surface water based irrigation or through managed aquifer recharge; however, nutrient leaching associated with increased recharge may adversely impact groundwater quality. Projected groundwater level recoveries range from 2 m yr^{-1} in the Piedmont and 0.8–1.5 m yr^{-1} in the deeper aquifer in the central plain [66] and projected reduced groundwater pumpage by ~6 km^3 yr^{-1}, 28% lower than current pumpage [44].

3.9. Implications for future food production

While many studies emphasize increasing irrigation and fertilization to meet rising food demand in different regions globally, more recent studies emphasize the importance of reducing environmental impacts of agriculture by optimizing management of water and nutrients [1, 9, 10]. The NCP–USHP comparison questions the returns from highly intensive management at the regional scale. Limitations of intensive management should be considered, including restrictions on crop growth period from double cropping, as seen in the NCP, and potential competing effects of intensive irrigation and fertilization leaching fertilizers below the crop root zone. Findings from the analysis of spatial data in this study combined with previous field and modeling studies in the NCP indicate potential over application of fertilizers and irrigation and highlight many other factors that contributed more to crop yield than fertilization and irrigation, such as better cultivars, increased plant densities, and improved soil fertility. These findings are consistent with findings of a recent global study that recognized the contribution of modern or high yielding crop varieties to yield growth in the late Green Revolution (1981–2000) [5]. Godfray *et al* [3] also emphasize the potential role of crop genetics in increasing crop yield based on the increasing speed and lower costs associated with sequencing and re-sequencing genomes to enhance crop yields in challenging environments. However, as many of the previous studies indicate, improvements in cultivars and breeding are linked to many of the other factors impacting crop yield, such as growing period length and planting dates, plant densities, soil fertility, fertilization, and irrigation. As the results of this study emphasize, many factors should be considered for increasing crop production in the future to reduce adverse impacts on water resources.

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