The Journal of Agricultural Science

cambridge.org/ags

Crops and Soils Research Paper

Cite this article: Liu X, Li S, He P, Zhang P, Duan Y (2018). Yield and nutrient gap analysis for potato in northwest China. *The Journal of Agricultural Science* **156**, 971–979. https://doi.org/10.1017/S0021859618000916

Received: 22 January 2018
Revised: 26 September 2018
Accepted: 8 October 2018
First published online: 28 November 2018

Key words:
Actual on-farm yield; attainable yield; nutrient gap; potato; yield gap

Author for correspondence:
Shutian Li, E-mail: sli@ipni.net

Yield and nutrient gap analysis for potato in northwest China

X. Liu[1], S. Li[1,2], P. He[1,2], P. Zhang[3] and Y. Duan[4]

[1]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 100081 Beijing, China; [2]International Plant Nutrition Institute (IPNI) Beijing Office, 100081 Beijing, China; [3]Dryland Agriculture Institute, Gansu Academy of Agricultural Sciences, 730070 Lanzhou, China and [4]Resources, Environment and Testing Institute, Inner Mongolia Autonomous Region Academy of Agricultural and Animal Husbandry Sciences, 010031 Hohhot, People's Republic of China

Abstract

Analysis of the potato yield gap and the corresponding nutrient gap can help in devising strategies and measurements to increase productivity for closing the gaps through improved practices. On-farm experiments conducted in the main potato production areas of northwest China were used to determine attainable yield. Official statistical data were used to determine the actual on-farm yield. Yield gap was the difference between attainable yield and actual on-farm yield. Nutrient gap was calculated by dividing the size of yield gap by partial factor productivity. Results indicated that nitrogen (N), phosphorus (P) and potassium (K) fertilization increased potato yield by an average of 1169–7625, 2937–5336 and 2331–7338 kg/ha, respectively. The maximum attainable yields (the 90th percentile yields) were 50 145, 37 855, 30 261 and 56 616 kg/ha and the average actual on-farm yield were 14 179, 16 732, 10 271 and 19 990 kg/ha in the Inner Mongolia Autonomous Region (IMAR), Gansu, Ningxia and Qinghai provinces, respectively. In the above four regions, yield would need to increase by 165, 70, 112 and 121% from actual yield to reach 75% of attainable yield. Compared with recent 3-year average NPK rates by farmers, the total NPK rates need to increase by 90.1–134.3% for IMAR, 42.9–69.2% for Gansu, 68.1–111.2% for Ningxia and 48.1–83.8% for Qinghai to improve productivity to near the 75% attainable yield. In conclusion, the high yield responses to fertilizer application provide opportunities to close the large yield gaps through balanced nutrition.

Introduction

The global population is expected to reach over 9 billion by 2050, providing a challenge to increase food production by 70–100% in order to meet increasing demand (van Wart *et al*., 2013; Svubure *et al*., 2015). Specifically, sufficient food supply has been the main concern in China due to its large and increasing population. Cropland areas in China have decreased gradually because of urbanization and economic development. Therefore, increasing crop production depends mainly on improving output from current cropland. Potato (*Solanum tuberosum* L.) is one of the main food crops and the Chinese government launched a strategy of potato staple food normalization to promote its production and consumption as the fourth major food crop following rice, wheat and maize. China's potato production is presently almost 100 million tonnes, making China the world's leading potato-growing nation. The northwest region of China produces nearly one-third of its annual harvest (MOA, 1982–2014). In future, potato will play an important role in China's food security.

Although China's northwest has great productive capacity, potato yield has been restricted by water shortages and imbalances of nutrient application. Increasing potato production through sustainable intensification depends on the yield gap between current actual (on-farm) yield and yield potential in a specific agroecological environment. Exploiting and narrowing the current yield gap through nutrient management is one way to increase potato production. Therefore, the first step is to determine yield potential and actual yield in a given region using scientific approaches and technologies.

Yield potential is the maximum attainable yield achieved under field conditions when all factors of crop management are as effective as possible (Svubure *et al*., 2015). The maximum attainable yield can be estimated by crop model simulation or obtained through field experiments; maximum farmer yields are based on surveys at a local level (Lobell *et al*., 2009; Van Ittersum *et al*., 2013). Multiple-year field experimental data have been used successfully to determine attainable yield for maize (Meng *et al*., 2013), wheat (Lu and Fan, 2013) and rice (Xu *et al*., 2016). More information about the region's attainable potato yield is needed to determine how it can best support increasing potato demand. The yield gap between attainable and actual yield could be closed through improved management practices.

Table 1. Characteristics of the field trials and soil properties

Items	IMAR	Gansu	Ningxia	Qinghai
Potato areas (ha)	512 000	665 000	171 000	90 000
No. of trials	288	170	84	114
No. of trials with irrigation	216	75	26	73
Growth period	May–September	April–October	April–September	May–September
Annual rainfall (mm)	211–549 (370)[a]	300–558 (424)	195–366 (318)	352–523 (425)
N rate (kg/ha)	45–450 (200)	37–240 (172)	90–150 (116)	27–248 (186)
P_2O_5 rate (kg/ha)	30–250 (99)	38–225 (97)	45–225 (125)	35–276 (93)
K_2O rate (kg/ha)	30–338 (139)	30–210 (91)	45–300 (154)	84–203 (123)
Soil type	Chestnut soil	Loess	Desert grey soil	Chestnut soil/sierozem
Organic matter (g/kg)	1.5–25.2 (10.3)	2.5–14.4 (7.3)	2.0–5.0 (2.6)	9.0–23.4 (14.4)
Mineral N (mg/l)	3.6–72.0 (23.6)	17.3–86.8 (46.2)	7.6–9.5 (8.6)	35.6–97.0 (56.1)
Available P (mg/l)	5.5–37.5 (15.8)	5.5–29.1 (19.7)	18.3–27.9 (24.1)	8.6–36.6 (26.3)
Available K (mg/l)	54.2–325 (104.4)	63.6–320.6 (175.5)	105–112 (109.4)	105.3–160.0 (132.9)

N, nitrogen; P_2O_5, phosphorus pentoxide; K_2O, potassium oxide; IMAR, Inner Mongolia Autonomous Region.
[a] Numbers in parenthesis represent the average.

Thus, the objectives of the current study were to: (1) quantify potato yield response to fertilization and nutrient use efficiency; (2) determine attainable yield, average actual on-farm yield and yield gaps of potato and (3) estimate nutrient gaps relative to yield gaps.

Materials and methods

Attainable yield

The multiple-year field experimental data, one of the four methods used at a local level (Van Ittersum *et al.*, 2013), were used to analyse and estimate attainable yields of potato. This included a total of 288, 170, 84 and 114 on-farm trials conducted since 2002 in the main potato production areas in Wuchuan county (111°45′N, 41°08′E, 1700 m asl), Wuyuan county (108°27′N, 41°10′E, 1050 m asl) and Linhe city (107°40′N, 40°75′E, 1038 m asl) of IMAR, Dingxi city (104°59′N, 35°46′E, 1985 m asl), Hezheng county (103°31′N, 35°43′E, 2000 m asl) and Jishishan (102°85′N, 35°74′E, 1700 m asl) of Gansu province, Tongxi county (106°39′N, 36°82′E, 1529 m asl), Xiji (105°73′N, 35°97′E, 1919 m asl) and Haiyuan county (105°65′N, 36°57′E, 1800 m asl) of Ningxia province, Huzhu county (101°95′N, 36°83′E, 2533 m asl), Ledu county (102°40′N, 36°48′E, 1974 m asl) and Gonghe county (101°40′N, 36°59′E, 2632 m asl) of Qinghai province (Table 1). Each trial had an optimum nutrient recommendation treatment (OPT) developed using the Agro Services International (ASI) 'systematic approach' (Hunter, 1980; Portch and Hunter, 2002), as well as corresponding nutrient omission treatments, e.g. without nitrogen (OPT-N), without phosphorus (OPT-P) and without potassium (OPT-K). Fertilizer recommendation rates varied greatly due to soil testing results and target yield. The amount of total NPK fertilizer applied in the OPT treatments ranged from 105–825 kg/ha in IMAR, 135–555 kg/ha in Gansu, 225–600 kg/ha in Ningxia and 186–588 kg/ha in Qinghai with averages of 438, 360, 395 and 402 kg/ha, respectively (Table 1). Potato cultivars used in the experiments were rounded white and oblong yellows, including Chinese selections such as Kexin (Su and Lai, 2007), Longshu (Wen *et al.*, 2007) and Qingshu (Zhang *et al.*, 2006).

Yield response to N, P or K fertilization was the difference between tuber yield obtained from OPT treatment and the respective yield from N, P or K omission treatment. Attainable yield was estimated from the yields of OPT treatments. Due to the arid climatic conditions in northwest China, it was reasonable to assume that reaching the 90th percentile yield threshold under an OPT treatment would mark the maximum attainable yield.

Actual on-farm yield

The actual on-farm yield was estimated using the method proposed by Van Ittersum *et al.* (2013) based on statistical data. Average actual on-farm yield was the crop yield achieved by farmers in a given agroecological region under the general management practices commonly used in the region (Cassman *et al.*, 2003).

In the current study, official statistical data from the Chinese Ministry of Agriculture between 1982 and 2014 (MOA, 1982–2014) were used to estimate the actual on-farm yield. These statistical data represented the average yield of all potato planted within regions, including both rainfed and irrigated potato, collected by farm surveys that were generally used to estimate actual yield (Haverkort *et al.*, 2014; Svubure *et al.*, 2015). The soil types, properties and growing conditions in the main potato production areas in the four provinces were similar to the experimental sites (Table 1). Sequential average on-farm yields, starting from the yield in 2014 and gradually including yield from earlier years, and the coefficient of variation (CV) was calculated. The minimum number of recent years with stable sequential average yield and lower CV were used to calculate the average actual on-farm yield.

Yield and nutrient gaps

The yield gap in a certain location is defined as the difference between attainable yield and average actual on-farm yield. The nutrient gap, i.e. the increase of nutrients required to increase yield and close the yield gap, was estimated based on nutrient PFP and the yield gap, i.e. N (P or K or NPK) gap = Yield gap/$\text{PFP}_{\text{N (P or K or NPK)}}$. The PFP was calculated as potato tuber yield obtained under

Table 2. Potato tuber yield response to nitrogen, phosphorus and potassium fertilizer application (kg/ha)

Location	Nutrient	Min	Lower quartile	Median	Upper quartile	Max	Mean	Std. dev.
IMAR	N	600	4100	7000	10 076	17 350	7625	4000
	P_2O_5	467	2471	4460	6217	16 975	5336	3928
	K_2O	200	1400	2467	4775	14 500	3598	3166
Gansu	N	50	2451	4611	6346	20 493	5542	4543
	P_2O_5	297	1649	2863	5060	14 578	3786	3201
	K_2O	121	1423	2733	4353	16 344	3128	2489
Ningxia	N	185	427	1128	1348	2611	1169	881
	P_2O_5	260	837	1426	2816	6141	2016	1554
	K_2O	75	847	2185	3305	5420	2231	1530
Qinghai	N	334	3300	7093	10 260	18 489	7228	4703
	P_2O_5	357	1161	2350	3938	7333	2937	2245
	K_2O	1666	4128	5828	9658	20 925	7338	4232

N, nitrogen; P_2O_5, phosphorus pentoxide; K_2O, potassium oxide; IMAR, Inner Mongolia Autonomous Region.

an OPT treatment divided by the amount of nutrient applied, i.e. PFP = potato yield/nutrient rate. The PFP_N, PFP_P, PFP_K and PFP_{NPK} represented PFP of N, P, K and NPK, respectively.

Statistical analysis

Statistical analysis and calculations, the relationship between potato yield and total fertilizer applied, relationship between PFP and nutrient application rate, relationship between tuber yield in OPT treatment and PFP, relationship between tuber yield and water supply, as well as sequential average actual on-farm yields and coefficients of variation were performed using Microsoft Excel. SigmaPlot14 (2017 Systat Software Inc.) was used to analyse the distribution of potato tuber yields from OPT treatments and to create the box plot.

Results

Identifying attainable potato yield

The network of field trials found great variations in tuber yield response to N, P and K fertilizer application throughout northwest China (Table 2). On average, N, P and K fertilization increased potato yield by 7625, 5336 and 3598 kg/ha in IMAR, by 5542, 3786 and 3128 kg/ha in Gansu, by 1169, 2016 and 2231 kg/ha in Ningxia and by 7228, 2937 and 7338 kg/ha in Qinghai, respectively.

The distribution of potato yields obtained with soil test-based OPT treatments varied considerably within and across regions (Fig. 1). In IMAR, Gansu, Ningxia and Qinghai, the average yields were 31 067, 26 935, 16 379 and 42 401 kg/ha, maximum yields were 61 250, 54 898, 34 335 and 69 033 kg/ha and the 90th percentile yields (the maximum attainable yields for this study) were 50 145, 37 855, 30 261 and 56 616 kg/ha, respectively. There were significant ($P < 0.001$) relationships between total NPK fertilizer rates and potato yields of OPT treatments conducted in IMAR and Ningxia, explaining 49 and 46% of the variation in tuber yield. Although there were increased trends of potato yields with increase of NPK fertilizer rates in Gansu and Qinghai the relationships were not significant (Fig. 2).

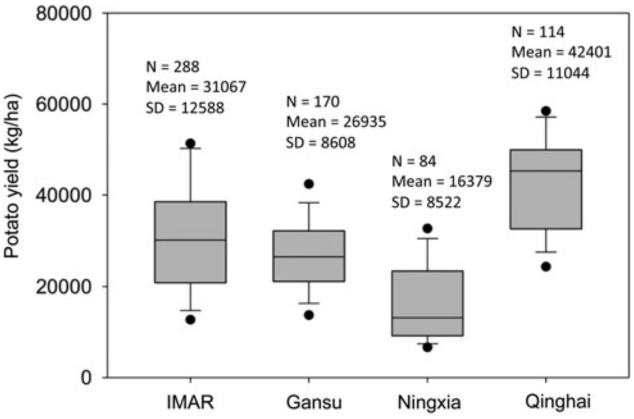

Fig. 1. Box plots showing the distribution of potato tuber yields in the IMAR and three provinces in northwest China resulting from optimum NPK recommendation treatments (box indicates lower quartile, median and upper quartile; error bars indicate 10th and 90th percentiles; solid circles indicate 5th and 95th percentiles; SD is standard deviation).

Nutrient PFP

The average PFP_N, PFP_P, PFP_K and PFP_{NPK} were 167, 331, 240 and 72.2 kg/kg for IMAR, 175, 324, 353 and 81.6 kg/kg for Gansu, 137, 132, 127 and 40.8 kg/kg for Ningxia and 272, 582, 374 and 110.3 kg/ha for Qinghai, respectively (Table 3). The PFP_N, PFP_P and PFP_K were significantly ($P < 0.001$) and negatively related to fertilizer N, P and K rates, respectively (Fig. 3).

Significant ($P < 0.001$) positive relationship existed between tuber yield of the OPT treatments and PFP_{NPK}, but the variations of tuber yield explained by these relations varied greatly with different nutrients and location (Fig. 4). The relationship could explain 13.9, 32.4 and 13.4% of tuber yield variations for N, P and K in IMAR, 25.4, 59.5 and 30.9% of tuber yield variations

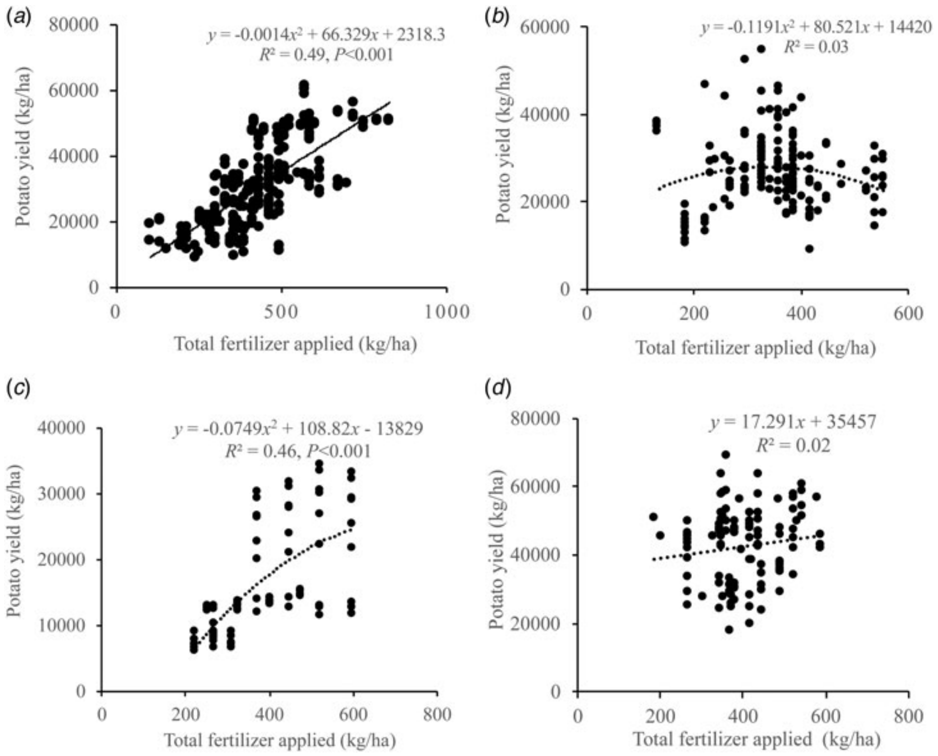

Fig. 2. Relationship between potato yield and total NPK fertilizer applied in the optimum NPK recommendation treatments in IMAR (a), Gansu (b), Ningxia (c) and Qinghai (d).

for N, P and K in Gansu, 79.9, 47.4 and 32.5% of tuber yield variations for N, P and K in Ningxia and 19.0, 19.5 and 70.3% of tuber yield variations for N, P and K in Qinghai.

Determination of actual on-farm yield

In northwest China, on-farm yield data from the Ministry of Agriculture show an increasing trend between 1982 and 2014 (Fig. 5(*a*)). The number of years utilized for estimation of average actual on-farm yield must avoid yield variability and the effect of technology and climate change. Sequential average on-farm yields and the corresponding CVs indicate that in IMAR and the three provinces, the average yields of the most recent 5 years (2010–2014) are similar to the average yields of most recent 13 years (2002–2014) and the CVs are relatively low (Figs 5(*b*) and (*c*)). Therefore, the most recent 5-year (2010–2014) yield averages, combining rain-fed and irrigated potato production, represent the actual on-farm yield and are 14 179, 16 732, 10 271 and 19 990 kg tuber/ha for the IMAR, Gansu, Ningxia, and Qinghai, respectively.

Determination of yield gap

Yield gap is the difference between attainable yield and the average actual on-farm yield. Information about attainable and on-farm yield indicates that there is considerable potential to increase potato production in all four regions studied. However, the magnitude of the yield increase required to narrow the yield gap differed greatly across regions (Fig. 6). In IMAR, Gansu, Ningxia and Qinghai yields would need to increase by 76.8, 13.1, 47.3 and 41.6% to close yield gap to 50% of attainable yield, by 165, 70, 121 and 112% to close yield gap to 75% of attainable yield, and by 254, 126, 195 and 183% to reach a threshold equal to 100% of attainable yield.

Estimation of nutrient gap

Adequate and balanced nutrient input is one of the most important factors that can contribute to the narrowing of any yield gap. In order to assess how current on-farm fertilization practices are impacting the size of each region's yield gaps, the amounts of N, P, and K fertilizer (i.e. nutrient gaps) needed to reach the 75% attainable yield threshold were estimated. The nutrient gaps were calculated by dividing the size of the yield gap by the PFP obtained for each nutrient at the lower quartile, median and upper quartile, which represent low, medium and high nutrient use efficiency scenarios, respectively (Table 4).

Compared with data for recent 3-year average rates of fertilizer application by potato farmer, in order to close the yield gap, N rates in IMAR, Gansu, Ningxia, and Qinghai need to increase by 67.7–101.6, 36.3–60.8, 30.4–56.2 and 48.6–80.6%, respectively. Similarly, P rates need to increase by 64.0–101.5, 21.2–43.9, 70.7–122.8 and 21.7–37.9%. Given the generally low K rates being used across the northwest region, K rates need to increase several-fold in order to balance with N and P to improve productivity to near the 75% attainable yield threshold. Considering the total combined NPK fertilizer rates for these regions, a 90.1–134.3% increase is recommended for IMAR, 42.9–69.2% for Gansu, 68.1–111.2% for Ningxia and 48.1–83.8% for Qinghai (Table 4). The suggested appropriate nutrient application rate is the sum of on-farm nutrient rate and the nutrient gap needed to close the yield gap between a target yield and actual on-farm yield. For example, in IMAR, assuming the potato target yield is 37 609 kg/ha (75% attainable yield), the average actual on-farm yield is 14 179 kg/ha, the PFP_N at lower quartile scenario is

Table 3. PFP of applied N, P and K fertilizer

	IMAR ($n = 288$)[a]	Gansu ($n = 170$)	Ningxia ($n = 84$)	Qinghai ($n = 114$)
PFP_N (kg tuber/kg fertilizer N)				
Min	46	40	68	87
Lower quartile	123	124	91	174
Median	151	153	142	221
Upper quartile	184	207	168	288
Max	429	622	229	1877
Mean	167	175	137	272
SD[b]	69.6	88.1	46.2	231.0
PFP_P (kg tuber/kg fertilizer P_2O_5)				
Min	82	77	50	152
Lower quartile	247	198	92	373
Median	342	292	140	505
Upper quartile	391	409	161	651
Max	667	915	220	1837
Mean	331	324	132	582
SD	117.1	169.2	44.0	338.4
PFP_K (kg tuber/kg fertilizer K_2O)				
Min	80.0	97	39	133
Lower quartile	176	190	76	230
Median	222	314	96	387
Upper quartile	280	435	166	471
Max	703	1750	401	704
Mean	240	353	127	374
SD	100.4	228.7	79.9	147.1
PFP_{NPK} (kg tuber/kg fertilizer NPK)				
Min	22	21	20	47
Lower quartile	56	57	31	79
Median	71	76	36	105
Upper quartile	84	93	50	137
Max	184	284	80	272
Mean	72	82	41	110
SD	23.1	42.3	14.8	38.8

IMAR, Inner Mongolia Autonomous Region.
[a]Number of observations.
[b]Standard deviation.

122.6 kg/kg N (Table 3) and the mean N rate by farmer is 188.1 kg/ha (Table 4), then:

$$\begin{aligned}\text{Yield gap (kg/ha)} &= 37609 - 14\,179\\ &= 23430\ \text{kg/ha}\end{aligned}$$

$$\begin{aligned}\text{Nitrogen gap (kg/ha)} &= \text{yield gap (kg/ha)}/\text{PFP}_\text{N}\\ &= 23\,430/122{\cdot}6\\ &= 191{\cdot}1\ \text{kg/ha}\end{aligned}$$

$$\begin{aligned}\text{The suggested N rate (kg/ha)} &= 188{\cdot}1 + 191{\cdot}1\\ &= 379{\cdot}2\ \text{kg/ha}\end{aligned}$$

The N gap and suggested rate at other scenarios, P, K or total NPK gap and the suggested rate can be also determined by this procedure.

Discussion

Generally, it is difficult to achieve maximum yield with greater uncertainty in factors such as temperature, rainfall and pest/

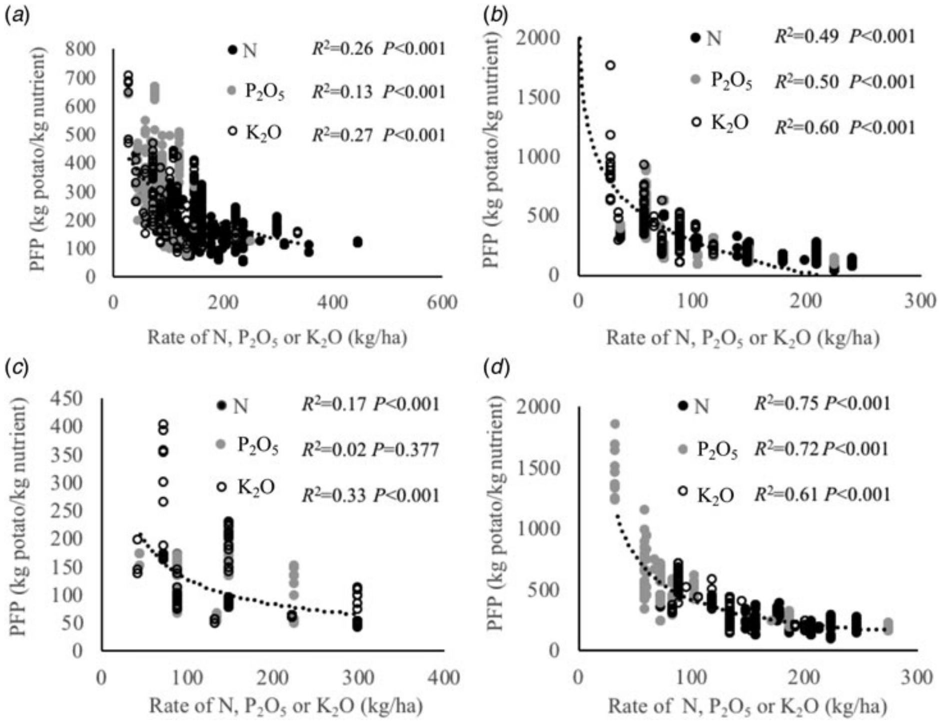

Fig. 3. Relationship between PFP of nutrient and the corresponding nutrient rate in IMAR (a), Gansu (b), Ningxia (c) and Qinghai (d).

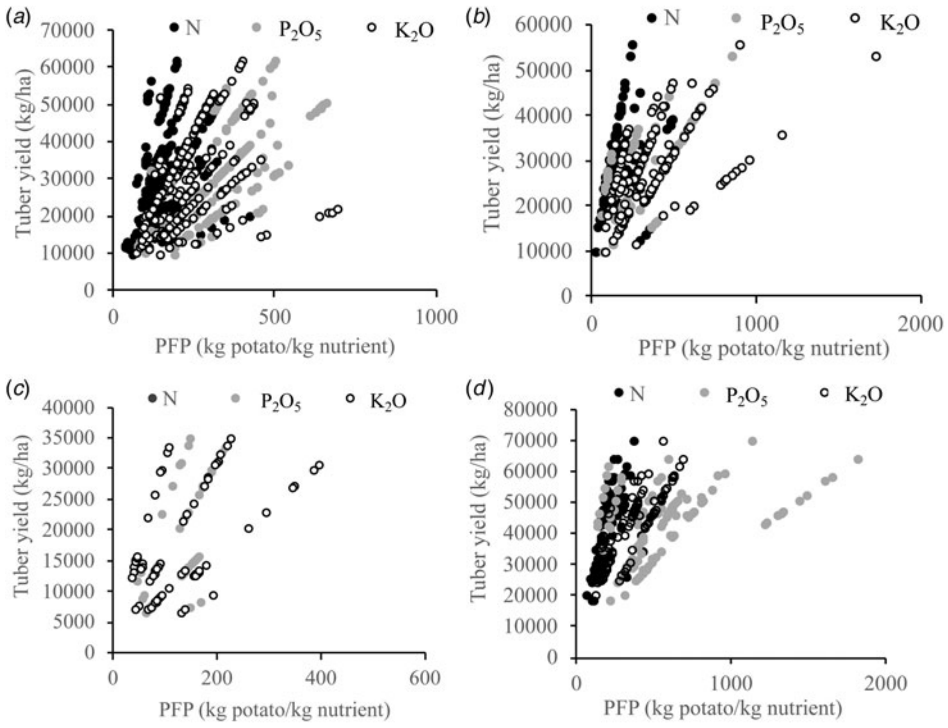

Fig. 4. Relationship between tuber yield in the optimum NPK recommendation treatment and PFP of nutrient in IMAR (a), Gansu (b), Ningxia (c) and Qinghai (d).

disease. Also, such high yields are not cost-effective because of diminishing returns when yields reach their ceiling (Koning *et al.*, 2008; Lobell *et al.*, 2009; van Wart *et al.*, 2013). The four provinces in northwest China are arid regions with annual rainfall typically <400 mm, which affects potato production greatly. It is reasonable to close yield gaps using a lower yield level. Therefore, the current study regards tuber yield at the 90th percentile in each province as maximum attainable yield.

PFP for applied nutrients reflects both indigenous soil nutrient productivity and yield increase by fertilization, so it is reasonable and practical to estimate nutrient gaps using PFP and yield gaps (Grzebisz *et al.*, 2012). The PFPs for applied N, P and K are significantly and negatively related to respective nutrient application rates, similar to results from Chile (Haverkort *et al.*, 2014) and Zimbabwe (Svubure *et al.*, 2015). In most cases, the high PFPs indicated low rates of applied nutrients and the soil might be mined for these

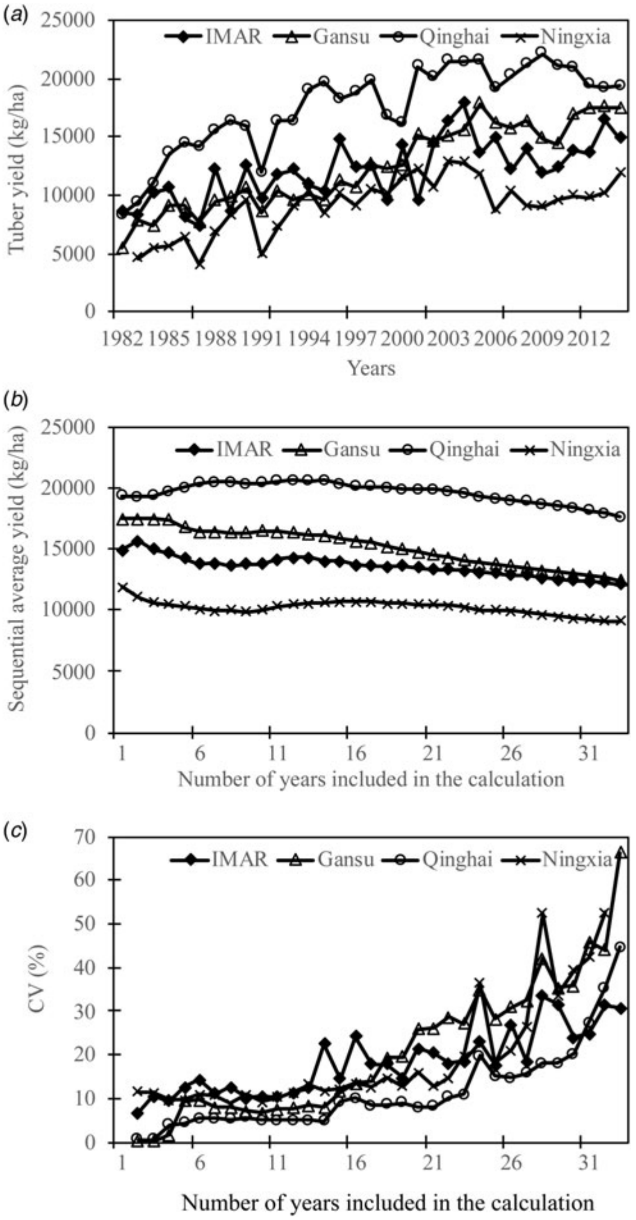

Fig. 5. Trends in actual on-farm potato yield from 1980 to 2014 (a), sequential average yields starting from the year 2014 and gradually including earlier years (b) and the associated coefficients of variation (c) for IMAR and three provinces in northwest China.

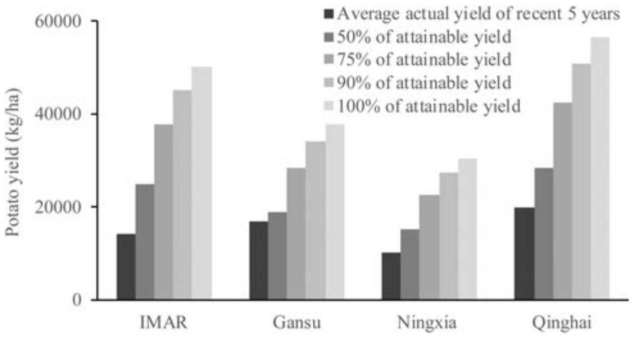

Fig. 6. Potato yield increase from closing yield gaps to 0.50, 0.75, 0.90 and 1.00 of attainable yields in IMAR and three provinces in northwest China.

Table 4. Projected nutrient gaps necessary to close yield gaps to 0.75 of attainable yields

	IMAR ($n = 288$)[a]	Gansu ($n = 170$)	Ningxia ($n = 84$)	Qinghai ($n = 114$)
PFP$_N$ scenarios[b]	N gaps, kg/ha			
Low	191.1	94.3	136.7	129.4
Medium	155.1	76.2	87.8	101.7
High	127.3	56.3	73.9	78.0
On-farm N rate[c]	188.1	155.1	243.4	160.6
PFP$_P$ scenarios	P_2O_5 gaps, kg/ha			
Low	95.0	59.0	134.5	60.2
Medium	68.5	40.0	88.5	44.5
High	59.9	28.5	77.4	34.5
On-farm P rate	93.6	134.4	109.5	158.7
PFP$_K$ scenarios	K_2O gaps, kg/ha			
Low	133.4	61.2	163.1	97.6
Medium	105.5	37.1	129.8	58.1
High	83.6	26.8	74.9	47.7
On-farm K rate	28.2	4.5	13.3	21.9
PFP$_{NPK}$ scenarios	$N + P_2O_5 + K_2O$ gaps, kg/ha			
Low	416.3	203.5	407.1	286.0
Medium	329.6	154.0	343.1	215.0
High	279.2	126.0	249.3	164.2
On-farm NPK rate	310.0	294.0	366.2	341.2

IMAR, Inner Mongolia Autonomous Region.
[a] Number of observations.
[b] Calculated under low (lower quartile), medium (median) and high (upper quartile) scenarios of PFP.
[c] Recent 3-year average fertilizer rates applied by potato farmers (NDRC, 2014).

minerals, especially in irrigated potato. In the current study, the significant positive relationships between tuber yields under OPT treatments and PFPs in the four locations indicate that higher tuber yields relate to higher PFP, suggesting high efficiency of applied nutrient at the recommended rate in the experiments.

There is considerable potential to increase potato production in these four regions. However, it is impossible and unnecessary for all farmers to achieve maximum attainable yield because of economic and environmental considerations (Koning *et al.*, 2008; Lobell *et al.*, 2009; van Wart *et al.*, 2013). It is reasonable to close yield gaps at a lower yield level threshold relative to yield potential, considering uncertainty over climatic conditions (Van Ittersum *et al.*, 2013). Therefore, in the current study nutrient gaps were estimated at 75% of maximum attainable yield under the arid climatic conditions and management level in northwest China. Mueller *et al.* (2012) also estimated the projected increase of nutrient rates to close maize, wheat and rice yield gaps to 75% of attainable yields.

In the current study, similar to other studies (Grzebisz *et al.*, 2012; Lu and Fan, 2013; Van Ittersum *et al.*, 2013), yield gap was calculated as the difference between attainable yield and

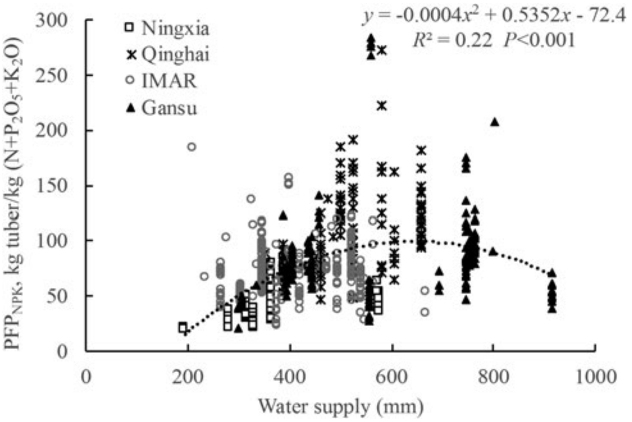

Fig. 7. Relationship between water supplies (annual rainfall plus irrigation) and PFP of NPK fertilizers (PFP_{NPK}).

average actual on-farm yield in a region, reflecting the potential of yield increase in a regional scale. This method might overestimate yield gaps because the average actual on-farm yield represents yields under various moisture, soil fertility and pest or disease control management conditions, reflecting situations of the whole area. Other studies (Xu *et al*., 2015, 2016) have estimated crop yield gaps as the difference between yields of balanced fertilization and farmer practice or nutrient omission treatments in the same experiment, reflecting the yield increase in the controlled situations, not the whole regional situations. This might under-estimate the yield gaps and be unsuitable for estimating yield gaps in regional or national scales.

Fertilization is one of the most important approaches to increase yield and close the yield gap to an attainable yield. Grzebisz *et al*. (2012) indicated that yield gap of wheat decreased with increased N application rate. The current study indicates that less than half of the variations in tuber yield could be explained by nutrient application rate, similar to the results of Haverkort *et al*. (2014) who showed that 45% of variation in actual potato yield was explained by fertilization. This information suggests a need for potato growers to focus on improving their management of other factors in addition to NPK fertilization (e.g. water management) in order to make the investment in fertilizer more effective.

Water supply is an important factor that influences potato yield, yield gap and nutrient use efficiency in the arid regions of northwest China. The relationship between PFP of total NPK nutrient and water supply indicates that water supply can explain 22% of the variation in PFP (Fig. 7), suggesting that improving water supply can increase nutrient use efficiency and then reduce the nutrient gaps needed to close the yield gaps. Studies showed that better water management could improve tuber yield and nutrient use efficiency (Li *et al*., 2011). Also, increasing irrigation area can increase potato yield in a whole region and contribute to narrowing the yield and nutrient gaps (Van Ittersum *et al*., 2013). Therefore, growers have an opportunity for significant potato yield increases through improving both nutrient and water management in northwest China.

Conclusion

High potato yield responses to N, P and K application provide the opportunities to close the large yield gaps through balanced crop nutrition. Closing the yield gap to 75% of the attainable yield is a realistic goal, which could be the expected response to application of about 43–134% more NPK compared with current practice. Water management is an alternative opportunity to closing the yield gap in the studied regions. It is desirable for narrowing the yield gap by integrated management of nutrient and water that need to be further studied.

Acknowledgements. The authors thank Soil and Fertilizer Institute of Qinghai Academy of Agriculture and Forestry Sciences, Institute of Agricultural Resources and Environment of Ningxia Academy of Agriculture and Forestry Sciences for their contribution to some field trials.

Financial support. The work was funded by the National Key Research and Development Project of China (2016YFD0200103) and the International Plant Nutrition Institute (IPNI).

Conflict of interest. None.

Ethical standards. Not applicable.

References

Cassman KG, Dobermann A, Walters DT and Yang HS (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources* **28**, 315–358.

Grzebisz W, Gaj R, Sassenrath GF and Halloran JM (2012) Fertilizer use and wheat yield in Central and Eastern European Countries from 1986 to 2005 and its implication for developing sustainable fertilizer management practices. *Communications in Soil Science and Plant Analysis* **43**, 2358–2375.

Haverkort AJ, Sandaña P and Kalazich J (2014) Yield gaps and ecological footprints of potato production systems in Chile. *Potato Research* **57**, 13–31.

Hunter AH (1980) *Laboratory and Greenhouse Techniques for Nutrient Survey to Determine the Soil Amendments Required for Optimum Plant Growth*. Florida, USA: Agro Service International.

Koning NBJ, Van Ittersum MK, Becx GA, van Boekel MAJS, Brandenburg WA, Van Den Broek JA, Goudriaan J, Van Hofwegen G, Jongeneel RA, Schiere JB and Smies M (2008) Long-term global availability of food: continued abundance or new scarcity? *NJAS – Wageningen Journal of Life Sciences* **55**, 229–292.

Li S, Duan Y, Guo T and Zhang Y (2011) Demonstrating a link between nutrient use and water management to improve crop yields and nutrient use efficiency in arid Northwest China. *Better Crops* **95**, 20–22.

Lobell DB, Cassman KG and Field CB (2009) Crop yield gaps: their importance, magnitudes, and causes. *Annual Review of Environment and Resources* **34**, 179–204.

Lu C and Fan L (2013) Winter wheat yield potentials and yield gaps in the North China Plain. *Field Crops Research* **143**, 98–105.

Meng Q, Hou P, Wu L, Chen X, Cui Z and Zhang F (2013) Understanding production potentials and yield gaps in intensive maize production in China. *Field Crops Research* **143**, 91–97.

Ministry of Agriculture PRC (MOA) (1982–2014) *China Agriculture Statistical Report*. Beijing, China: China Agriculture Press.

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N and Foley JA (2012) Corrigendum: closing yield gaps through nutrient and water management. *Nature* **490**, 254–257.

National Development and Reform Commission PRC (NDRC) (2014) *National Agricultural Product Cost and Income Data Compilation*. Beijing, China: China Statistics Press.

Portch S and Hunter A (2002) A Systematic Approach to Soil Fertility Evaluation and Improvement. Beijing, China: PPI/PPIC China Program. pp 30–44.

Su XT and Lai LB (2007) Performance of potato variety Kexin No. 18 sown in winter and its high-yielding cultivation techniques. *China Potato Journal* **21**, 118–119 (in Chinese).

Svubure O, Struik PC, Haverkort AJ and Steyn JM (2015) Yield gap analysis and resource footprints of Irish potato production systems in Zimbabwe. *Field Crops Research* **178**, 77–90.

Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P and Hochman Z (2013) Yield gap analysis with local to global relevance – a review. *Field Crops Research* **143**, 4–17.

Van Wart J, Kersebaum KC, Peng S, Milner M and Cassman KG (2013) Estimating crop yield potential at regional to national scales. *Field Crops Research* **143**, 34–43.

Wen GH, Wang YH and Li GF (2007) A new potato variety: 'Longshu no. 6'. *China Vegetables* **6**, 29–31 (in Chinese).

Xu X, Liu X, He P, Johnston AM, Zhao S, Qiu S and Zhou W (2015) Yield gap, indigenous nutrient supply and nutrient use efficiency for maize in China. *PLoS ONE* **10**, e0140767. https://doi.org/10.1371/journal.pone.0140767.

Xu X, He P, Zhao S, Qiu S, Johnston A and Zhou W (2016) Quantification of yield gap and nutrient use efficiency of irrigated rice in China. *Field Crops Research* **186**, 58–65.

Zhang YC, Na TC, Shi L, Sun HL and Yuan JP (2006) Selection of a new potato variety Qingshu no. 8. *China Potato Journal* **20**, 380–381 (in Chinese).