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An Evaluation of Potato Fertilization and the Potential of Farmers to Reduce the Amount of Fertilizer Used Based on Yield and Nutrient Requirements

Yayi Wang [1,2,†], Rong Zhang [2,†], Songling Li [2], Xinnian Guo [3], Quanhui Li [2], Xiaoli Hui [1], Zhaohui Wang [1,4,*] and Huixia Wang [5]

1 College of Natural Resources and Environment, Northwest A&F University, Xianyang 712100, China; 2010990020@qhu.edu.cn (Y.W.); xlhui0703@163.com (X.H.)
2 Academy of Agriculture and Forestry Sciences, Qinghai University, Xining 810016, China; 1997990031@qhu.edu.cn (R.Z.); 1997990027@qhu.edu.cn (S.L.); liquanhui_2008@163.com (Q.L.)
3 Institute of Agricultural Resources and Environment, Academy of Agriculture and Forestry Sciences of Ningxia, Yinchuan 750002, China; gxnian@163.com
4 State Key Laboratory of Crop Stress Biology for Arid Areas, Northwest A&F University, Xianyang 712100, China
5 Rural Industry Development Guidance Center of Qinghai Province, Xining 810016, China; 15309713287@189.cn
* Correspondence: w-zhaohui@263.net
† These authors contributed equally to this work.

Abstract: Unreasonable fertilization often fails to match crop yield and nutrient requirements, leading to low crop yield, the waste of mineral resources, and increased costs for farmers. A survey of the potato yield and fertilization of farmers was conducted in Haidong City of Qinghai Province for three consecutive years (2017–2019) torecommend reasonable fertilizer application. The results showed that the required amount of NPK fertilizer per ton of potato was 4.85 kg N, 1.26 kg P_2O_5, and 6.98 kg K_2O, respectively. The potato yields ranged from 7500 to 66,429 kg ha^{-1}, with an average of 26,069 kg ha^{-1}. The average N, P, and Kfertilizers (in the form of N, P_2O_5, and K_2O, respectively) applied by the farmers were 213 kg N ha^{-1}, 202 kg P_2O_5ha^{-1}, and 43 kg K_2O ha^{-1}. More than 60% of the farmers appliedtoo much Nand Pfertilizers and too little Kfertilizer. Therefore, the farmers with lowyieldsshould reduce the application of Nand P fertilizers by a range of 41–220 kg ha^{-1} and 24–265 kg ha^{-1}. Allthe farmers should increase Kfertilizer use by 7–273 kg ha^{-1}. Reasonable fertilization could effectively conserve resources, improve economic efficiency, and reduce environmental impact.

Keywords: yield range; high-yield management; fertilization evaluation; fertilizer reduction

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1. Introduction

Potato (*Solanum tuberosum* L.) is the fourth largest food crop in the world and plays an irreplaceable role in ensuring food security [1]. High nutrition (carbohydrates, protein, dietary fiber, vitamins, minerals, amino acids, etc.), easy digestibility, bulk quantity production, etc., have made potato the most popular vegetable in the world [2]. China is the world's largest potato producer, accounting for nearly a quarter of global potato production [3]. As the fourth major staple food in China, about 7.0 million ha were planted potatoes in China in 2023, and the total output reached 90 million tons [4].

Due to the limitation of mineral resources, the lack of fertilizer productivity has led to low food production in many places, and nearly one-sixth of the world's population still faces food shortages [5]. Research on nutrient management around the world shows that that the amount of fertilizer applied in China is higher than the amount of nutrients absorbed by the crop, and there is a lowerrate of fertilizer utilization. The waste of resources is more serious, and there are greater environmental risks [6]. First, the amount of nutrients from the fertilizer is lower than the amount of nutrients taken away by the crops. The growth and development of crops consume the original nutrients in the soil, and there is a severe. In the arid area of Longzhong, Gansu, 50% of the farmers appliedlow amounts of Nitrogen and phosphorus (in the form of N and P) fertilizers, and more than 70% of the farmers applied low amounts ofpotassium (in the form of K) fertilizer [7]. The farmers who planted potatoes in the dryland in the Yinshan Hilly Area of Inner Mongolia used too high or low amounts of P fertilizer, and there was very low use of K fertilizer overall [8].

Potatoes are primarily grown in the drylands of China, which have relatively severe growth environments and poor agricultural facilities. Most of them are planted by individual farmers who have different farming and fertilization management practices and little understanding of scientific cultivation, which severely limits the potential for potato yields. Among the factors that determine potato growth and yield, fertilization management stands out [9]. After fertilizer is applied to the soil, nutrients are provided in mineral forms and are readily available in the soil to facilitate absorption by the shallow root systems of potato varieties and enhance plant resistance and photosynthesis efficiency [10–12]. N, P, and K are the three major elements of crop growth, in which N accounts for 1% to 4% of plant dry matter and is absorbed from the soil as nitrate (NO_3^-) or in ammonium (NH_4^+) form, and it is regarded as the primary force behind plant development, including the development potatoes [13]. The majority of potato growers depend on P in the form of diammonium phosphate (DAP) and N in the form of urea [14]. Moreover, K has a crucial role in the higher productivity of potato tubers because it plays an important role in photosynthesis, regulation of opening and closing of stomata, and favoring high energy status, which helps in timely and appropriate nutrient translocation and water uptake in plants [15]. With the development of science and technology, the use of organic fertilizers is gradually increasing, and a careful combination of organic and inorganic sources of nutrients might be helpful to obtain a good economic return with excellent soil health [16]. While fertilization plays an important role in ensuring food security, over-fertilization will reduce crop yields, accelerate soil acidification, increase greenhouse gas emissions, and ultimately reduce economic income [17–20]. Organic farming has less negative impact on the environment than conventional farming based on chemical fertilizers [21].The long use of mineral fertilizers has caused irreparable damage to soil structures, mineral cycles, soil microbial flora, and plants [22–24]. Intensified N fertilization decreased the content of dry matter and starch in potato tubers [25,26]. At the same time, excessive fertilizer usage leads to the waste of resources, reduction of biodiversity, and environmental pollution [27–29], which restricts agricultural production.

Therefore, it is highly significant to be knowledgeable about the current situation of potato cultivation and the weakness of nutrient management to ensure stable crop yields, high nutrient efficiency, and environmental friendliness. Between 30 and 50% of crop production can be attributed to fertilizer nutrient inputs [30], which is enough to illustrate the importance of fertilizer inputs. However, the level of fertilization varies greatly in different places. Without considering the fertility status of the soil, the environment, and the type of varieties used, the Ethiopian Agricultural Institution (EIAR) generally recommends farmers use the blanket rate of 195 kg ha^{-1} of DAP and 165 kg ha^{-1} of urea, which sums up to account for 111 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} to satisfy the P and N requirements of potato, respectively [31]. More than 50% of the potato farmers in the mountainous areas of southern Ningxia applied excessive amounts of N fertilizer and low amounts of P fertilizer [32]. The general situation of potato fertilization in Shaanxi Province over a four-year period involved the use of excessive amounts of N, while those of P and K were inadequate [33]. The application of N, P, and Kin the Shanxi province wasbelow moderate levels [34]. More than 50% of the potato farmers in Qinghai applied excessive amounts of N and P fertilizers and insufficient amounts of K [35]. This questionnaire survey showed that potatoes are frequently fertilized unreasonably. Haidong City is the primary area for the production of potatoes in Qinghai Province, with an average yield of 25,199 kg ha^{-1} and average rates of application of 222 kg Nha^{-1}, 234 kg P_2O_5 ha^{-1}, and 59.7 kg K_2O ha^{-1}. A total of 67.7% of the farmers applied excessive amounts of N fertilizer, 81.0% of the farmers applied excessive amounts of P fertilizer, and 83.5% of the farmers applied insufficient amounts of K fertilizer [35]. However, Zhang et al. (2011) reported that the average yield of potatoes in Haidong City was 25,036 kg ha^{-1}, and the average amount of N and P applied to potatoes were 239 kg Nha^{-1} and 137 kg P_2O_5 ha^{-1}, respectively [36].Approximately 40% of the potato farmers applied low amounts of N fertilizer, and approximately 50% of the potato farmers applied low amounts of P fertilizer. It is apparent that the survey results in the same area are very different, particularly the results on the amount of P fertilizer used, which affects the judgment of farmers regarding fertilization. In order to give farmers scientific fertilization recommendations, it is necessary tofind out the fertilization habits and yield status of farmers. The main objectives of this study were to (i) investigate theamount of NPK fertilizer per ton of potato; (ii) clarify thefertilization methods of farmers, their potato yields, and the relationship between yield and fertilization; and (iii) identify the reasonable fertilization of NPK. This study will provide help to support the sustainable production of dryland potatoesand reduce environmental impact.

2. Materials and Methods

2.1. Source of the Data on Nutrient Requirements for Potatoes

Based on the results of multiple years of field experiments and an analysis of data frompprevious studies (Sections 2.3–2.5), this study aimed to establish a regression relationship between the application of N, P, and K; yield; potato variety; and the requirements of potato in terms of N, P, and K.

2.2. Overview of the Research Area

The survey area was located inHaidong City of Qinghai Province between 100°41.5′–103°04′ E and 35°25.9′–37°05′ N. The eastern part of the survey area was adjacent to Gansu Province. The administrative regions of Haidong City include two municipal districts and four autonomous counties, namely the Ping'an District and Ledu District and Minhe, Xunhua, Huzhu, and Hualong Counties. The survey area was 200 km long from east to west and 180 km wide from north to south, with a total area of 13,200 ha. The survey area includes the Ledu District, Minhe Hui and Tu Autonomous County, and Huzhu Tu Autonomous County. The climate of Haidong City is a semiarid continental climate, with the lowest altitude of 1650 m and the highest altitude of 4636 m. Most agricultural areas are in the range of 2200–3000 m. The average annual temperature is 0.3–13.8 °C, with an average of 6.2 °C [37], and the average annual rainfall is 200–400 mm. When Ledu District of Haidong City is utilized as an example, the average annual rainfall was 323 mm over the past 20 years (Figure 1a), and the average rainfall was 288 mm during the period of potato growth from April to September (Figure 1b), with substantial variation between the years. In the past 20 years, the rainfall over10 years only exceeded the average of Haidong City and the provincial average of 400 mm in 2007 and 2008. The maximum rainfall occurred in 2007 at 417 mm, and the minimum rainfall in 1996 was 261 mm. A total of 70.8% of the annual rainfall is distributed from June to September, with only 0.7–13.7% of the precipitation during the sowing period, which is less than 10% in most years. There is little rainfall, and it is unevenly distributed.

Potatoes are widely planted in Xining City, Haidong City, and six major prefectures in Qinghai Province. Approximately 91.5% of the potatoes are planted in Haidong City and Xining City (Figure S1), while the other six prefectures only comprise 8.5%. HaidongCity has the largest planting area, which accounts for 69.2% of the total area planted for potatoes in the province, and 93.6% of the potatoes are planted in mountainous and arid areas and rely primarily on rainfall.

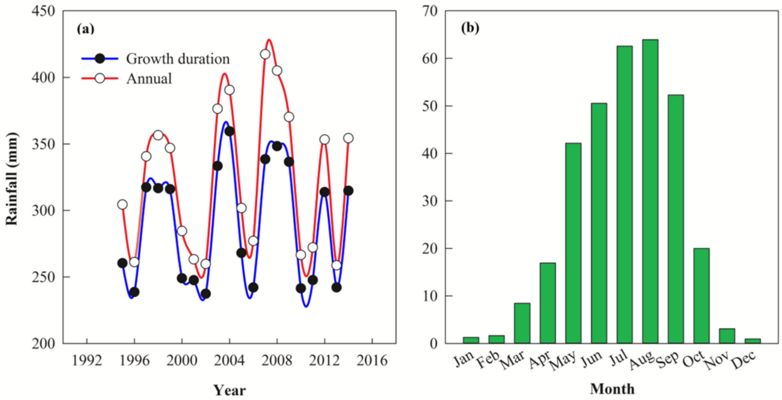

Figure 1. General condition of rainfall in the Ledu District of Haidong City during the past 20 years. Figure (**a**) shows the change in annual rainfall and rainfall during the potato growing season between 1995 and 2014, and figure (**b**) shows the change in average rainfall for each month over a 20-year period.

Only one crop can be planted per year in Qinghai Province, with a growing season from March to October and a fallow period from November to February of the following year. The potatoes are planted in two manners, including autumn (mulching) planting and top cover (mulching) planting. Autumn (mulching) planting involves consolidation of the field and fertilization (mulching) when the current crop is harvested in October. The seeds are sown from March to May of the next year. Top cover (mulching) planting refers to the consolidation of land and fertilization after the previous crop is harvested. The new crop is then sown from March to May of the next year. The soil in which the potatoes in Haidong City are planted is primarily sandy loam. The potatoes are primarily planted by individual farmers, and a few are managed by cooperatives on a large scale.

2.3. Study of Potato Yield, Nutrient Efficiency, and Economic and Environmental Benefits under the Comprehensive Optimization of Fertilization and Cultivation

These experiments were conducted in the mountainous region and dryland of the Ledu District in 2017–2019 and Minhe County in 2020. Three treatments were established in the experiment (Table 1), including farmer management, high-yield management, and high-efficiency management (Table 1). Each management had a community area of 300 m^2, and each treatment was repeated four times. The soil of the experimental site is sandy loam soil. The chemical properties of the soil are shown in Table 2 [38]. The potato varieties used in this study wereLeshu No. 1in Ledu District and Minshu No. 2 in Minhe County. The crops were sown before April 10 of each year in Ledu District and before 23 April in Minhe County with an amount of 2250 kg ha^{-1}. The potatoes were harvested in middle and late September. The ridge width was 70 cm, and the trench width was 30 cm in the treatments of high-yield management and high-efficiency management.

Table 1. Rates of fertilizer applied to the potato field during four growthseasons in dryland conditions.

Year	Treatment	Fertilizer Application (kg ha^{-1})		
		N	P_2O_5	K_2O
2017 2018	Farmer management (flat cropping, no film)	239	345	0
	High-yield management (semi-film ridgecultivation)	240	210	150
	High-efficiencymanagement (semi-film ridgecultivation)	180	158	113
2019 2020	Farmer management (flat cropping, no film)	239	345	0
	High yield management (semi-film ridgecultivation)	240	210	150
	High-efficiencymanagement (semi-film ridgecultivation)	216	189	135

Note: Fertilizers specific to high-yield management and high-efficiency management were applied with content of N 16%, P_2O_5 14%, and K_2O 10%. The types of fertilizer used in the farmer management were urea and DAP, and 70% of urea was applied during the seedling stage.

Table 2. Chemical properties of the 0–20 cm soil layer in experimental site.

Area	Total N	Total P	Total K	Alkali-Hydrolyzed N	Available P	Available K	Organic Matter	pH
	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(g kg^{-1})	
Ledu	1.4	2.1	24.6	92.0	21.0	167.0	18.1	8.1
Minhe	1.7	2.0	24.0	59.0	12.0	80.0	21.1	8.2

A total of 3200 kg ha^{-1} of commercial manure was applied for the high-efficiency management treatment each year. The manure contained N 3.6%, P_2O_5 1.2%, and K_2O 2.0%. All the fertilizers were applied at the base. They were completed at the ridge, and for fertilization, mulch film and seedings were applied by hand in the high-yield management treatment, while amachine conducted all these treatments at once duringthe treatment of high-efficiency management. Both treatments were covered with a white film. The mulching film was not removed, so it would retain moisture in all the treatments after the previous crop had been harvested. All the potato farming activities wereconducted during the following spring, and the land was prepared 1week before sowing.

2.4. Slow-Release Fertilizer Study in Haidong City in Qinghai Province

This study was established as nine treatments (Table 3). Each treatment was repeated three times. The area of each replicate was 30 m^2, and the blocks were randomly arranged. The soil nutrient content was 1.2 g kg^{-1} of total nitrogen (TN), 1.85 g kg^{-1} of total phosphorus (TP), 25.8 g kg^{-1} of total potassium (TK), 69.0 mg kg^{-1} of alkali-hydrolyzed nitrogen, 3.8 mg kg^{-1} of available phosphorus (AP), 74.0 mg kg^{-1} of available potassium (AK), and 18.3 g kg^{-1} of organic matter (OM), respectively. The pH was 8.2. The potatoes were sown on 22 April 2016 and harvested on 5 October 2016. The potato variety Minshu 2 was utilized in this experiment, and it was sown at a rate of 2250 kg ha^{-1}. The large ridge width of the whole film planting was 70 cm, and the small ridge was 40 cm.

Table 3. Design of the rate of application for the slow-release fertilizer experiment.

Treatment	Fertilizer Application (kg ha^{-1})			Fertilization	
	N	P_2O_5	K_2O	Urea (kg ha^{-1})	Slow-Release Urea (kg ha^{-1})
1	240	210	150	-	-
2	0	210	150	-	-
3	240	210	150	522.0	-
4	240	210	150	105.0	(60 days) 417.0
5	192	210	150	84.0	(60 days) 334.5
6	240	210	150	105.0	(90 days) 417.0
7	192	210	150	84.0	(90 days) 334.5
8	240	210	150	105.0	(120 days) 417.0
9	192	210	150	84.0	(120 days) 334.5

Note: -, fertilizer was not applied. K_2O, potassium oxide; N, nitrogen; P_2O_5, phosphorous pentoxide.

Fertilizer specific to potatoes was applied in the first treatment, with contents of N, P_2O_5, and K_2O of 16%, 14%, and 10%, respectively. In the other treatments, 1751 kg ha^{-1} of superphosphate was applied, and that of potassium sulfate was 300 kg ha^{-1}. Treatments 4 to 9 were treated with different amounts of fast-available urea and slow-release urea. The content of fast-available urea N is 46%, the content of superphosphate P_2O_5 is 12%, and the content of potassium sulfate K_2O is 50%.

The principles for selecting the data from the previous studies were as follows: (1) The experiment was a field experiment. (2) The data included the amount of N, P, and K applied; the yield;total accumulation of N, P, and K in the plants; cultivation measures; potato varieties tested; and the N, P, and K requirements of the potatoes. (3) This study was conducted in the required area.

2.5. Water Retention Agent Experiment in Haidong City in Qinghai Province

The experiment was conducted in 2017 and 2018 in Ledu District, and Leshu No. 1 was the variety used. In 2017, three treatments were set up, and the K dosage of all treatments was the same. The main purpose was to explore the water retention effect of potassium magnesium sulfate, organic fertilizer, and water retention agents. In 2018, four treatments were set up to study the water-retaining effect of organic fertilizer alone, water-retaining agent alone, and organic fertilizer water-retaining agent mixed application (Table 4). Each treatment was repeated three times, and each repetition covered 30 m^2. The soil was sandy loam, with contents of 1.5 g kg^{-1} of TN, 85.0 mg kg^{-1} of alkali-hydrolyzed nitrogen, 6.1 mg kg^{-1} of AP, 247.0 mg kg^{-1} of AK, 18.3 g kg^{-1} of OM, and pH 8.5, respectively. The potatoes were sown on 5 April and harvested on 22 October. The variety Minshu 2 was used, and it was sown at a rate of 2250 kg ha^{-1}. The large ridge width of the whole film planting was 70 cm, and the small ridge width was 40 cm. The content of K_2O in potassium magnesium sulfate was calculated as 24%, and the content of K in potassium sulfate was calculated as 50%. There was 18% N and 46% P_2O_5 in the DAP, and the content of N, P_2O_5, and K_2O in the special fertilizer was 16%, 14%, and 10%, respectively.

Table 4. Application rate of the fertilizers for the water retention agent trial.

Year	Treatment	Potassium Sulfate (kg ha^{-1})	Potash Magnesium Sulfate Fertilizer (kg ha^{-1})	Organic Fertilizer (kg ha^{-1})	Water Retention Agent (kg ha^{-1})	Special Fertilizer (kg ha^{-1})	Organic Water Retention Agent Fertilizer (kg ha^{-1})
2017	1	0	681	3000	150	-	-
	2	327	-	-	-	-	-
	3	-	-	3000	-	1125	-
2018	1	327	-	-	-	-	-
	2	327	681	3000	150	-	-
	3	327	681	-	-	-	3150
	4	327	681	-	-	-	300

Note: -, fertilizer was not applied. Potassium magnesium sulfate contains K_2O 50%. DAP contains 18% N and 46% P_2O_5. Special fertilizer contains 16% N, 14% P_2O_5, and 10% K_2O. The content of K_2O in potassium magnesium sulfate was calculated as 24%.

Note: -, fertilizer was not applied. Potassium magnesium sulfate contains K_2O 50%. DAP contains 18% N and 46% P_2O_5. Special fertilizer contains 16%N, 14%P_2O_5, and 10%K_2O. The content of K_2O in potassium magnesium sulfate was calculated as 24%.

2.6. Databases for the Nutrient (N, P, and K) Requirements of Potatoes

In this study, there were 242 and 106 databases for the nutrient (N, P, and K) requirements of potatoes under conditions with and without N application, respectively. Similarly, there were 239 and 109 databases for the nutrient (N, P, and K) requirements of potatoes under conditions with and without P application. Additionally, there were 220 and 128 databases for the nutrient (N, P, and K) requirements of potatoes under conditions with and without K application. Furthermore, a total of 327 datasets corresponded to yield and potato nutrient requirements; likewise, variety selection in relation to potato nutrient requirements had a total of 342 datasets; finally, cultivation practices also had a total of 196 datasets.

2.7. Research Content

From 2017 to 2019, multi-year potato planting research was conducted in the Ledu District, Minhe County, and Huzhu County of Haidong City for three consecutive years. A total of 120 households were surveyed each year, which resulted ina total of 361 households. A questionnairewas providedto inquire about and record information on the area of potato planting variety, basic farmland conditions, previous crops, cultivation methods, sowing situation, field management, fertilization period, fertilization amount, fertilization method, and crop yields.

2.8. Yield Grading Method

The yields of potatoes from the survey were between 7500 and 66,500 kg ha^{-1}, and 90% were in the range of 12,450–39,000 kg ha^{-1}. When 5% and 95% of the potato yield were considered to be the minimum and maximum limits, the difference was calculated and divided into five levels with equal intervals [39].The production of potatoes from low to high was divided into the following categories: <17,760 kg ha^{-1} (very low), 17,760–23,070 kg ha^{-1} (low), 23,070–28,380 kg ha^{-1} (moderate), 28,380–33,690 kg ha^{-1} (high), and >33,690 kg ha^{-1} (very high).

2.9. Fertilizer Classification and the Recommended Amount of Fertilizer for the Farmers

The classification standard of the amount of fertilizer that farmers should apply was determined from previous studies. Based on the results of local fertilization tests, the recommended fertilizer amount was taken as a reasonable range, and the classification was taken as a variable amplitude of 20% [40]. This method led to the selection of 150 kg Nha^{-1}, 105 kg P_2O_5 ha^{-1}, and 75 kg K_2Oha^{-1} as the optimal rates of fertilization. The rates of N, P (P_2O_5), and K (K_2O) were divided into five levels (Table 5).

Table 5. Nutrient requirements, yield, and amount of fertilizerof different potato varieties.

Level	N Rate (kg ha^{-1})	P_2O_5 Rate (kg ha^{-1})	K_2O Rate (kg ha^{-1})
Very low	<120	<55	<35
Low	120–150	55–105	35–75
Moderate	150–180	105–155	75–115
High	180–210	155–205	115–155
Very high	>210	>205	>155

2.10. Calculation and Statistical Analysis

All statistics were completed in SPSS version 22.0 (IBM SPSS Statistical, Chicago, IL, USA). The coefficients of variation of the demand for NPK in the potato cultivars were calculated. Sigmaplot version 12.5 (Systat, San Jose, CA, USA) and Origin Pro version 2016 (OriginLab, Wellesley Hills, MA, USA) were used to drawgraphs and regression analyses.

$$\text{Nitrogen (phosphorus, potassium) demand (kgt}^{-1}\text{) = aboveground nitrogen (phosphorus, potassium) accumulation/yield (kg ha}^{-1}\text{)} \times 1000$$

$$\text{Recommended fertilizer application amount (kg ha}^{-1}\text{) = the average yield of each grade (kg ha}^{-1}\text{)} \times \text{the nutrient requirements of potato (kgt}^{-1}\text{)/1000}$$

3. Results

3.1. Nutrient Requirement of Potato and Its Influencing Factors

An analysis of the data from multi-site experiments for many years and previous studies showed that the requirements of N, P, and Kin potato production were 4.85 kg Nt^{-1}, 1.26 kg $P_2O_5t^{-1}$, and 6.98 kg K_2Ot^{-1}, respectively, and the ratio of N, P, and K was 1:0.25:1.44.

The coefficients of variation of the demand for NPK in the potato cultivars were 45.9%, 57.6%, and 56.8%, respectively, indicating that the demand for NPK varied greatly among the different varieties (Table S1).

The relationship between the rate of N applied and the demand for N, P, and K by the potatoes was analyzed (Figure 2a–c), and the demand of the potato for N was the lowest when the rate of N applied was 150–180 kg ha^{-1} (moderate), with an average of 3.72 kg kg^{-1}. A rate of low or high N led to an increase in the potatoes' demand for N, which increased by 16.4% and 28.0%, respectively. The effect of N fertilizer on the demand for P manifested as a trend of first increasing and then decreasing with the increase in fertilizer use. When a high rate of N was applied (180–210 kg ha^{-1}), the demand for P was the highest at 3.79 kg P_2O_5 kg^{-1}, and when a very high rate of N was applied (>210 kg ha^{-1}), the demand for P was very high (210 kg ha^{-1}). The demand for P was the lowest at 1.20 kg P_2O_5 kg^{-1}. There was no obvious pattern of the effect of N fertilizer inputs on the demand of K, and the highest demand for K was 5.52 kg K_2O kg^{-1} at 120–150 kg ha^{-1} (low) and the lowest at 180–210 kg ha^{-1} (high) at 3.80 kg K_2O kg^{-1}. When the low amounts of N were applied, the demand for N, P, and K increased by 16.4%, 44.9%, and 49.5%, respectively. The demand for N, P, and K in the potatoes increased and then decreased with the increase in phosphate fertilizer (Figure 2d–f). There was a decrease in the demand for N, P, and K when there was a high amount of P fertilizer, and the demand increased when there was a low amount of P fertilizer. The two were inversely proportional. The highest demand for N and Pin the potatoes occurred when 105–155 kg ha^{-1} (moderate) of K was applied, and it reached 4.63 kg N kg^{-1} and 2.03 kg P_2O_5 kg^{-1}, and the demand for potassium was as high as 6.90 kg K_2O kg^{-1} when 55–105 kg ha^{-1} (low) of P was applied. The lowest requirement for N, P, and K was 3.63 kg N kg^{-1}, 1.06 kg P_2O_5 kg^{-1}, and 4.08 kg K_2O kg^{-1} when the rate of P applied > 205 kg ha^{-1} (very high).

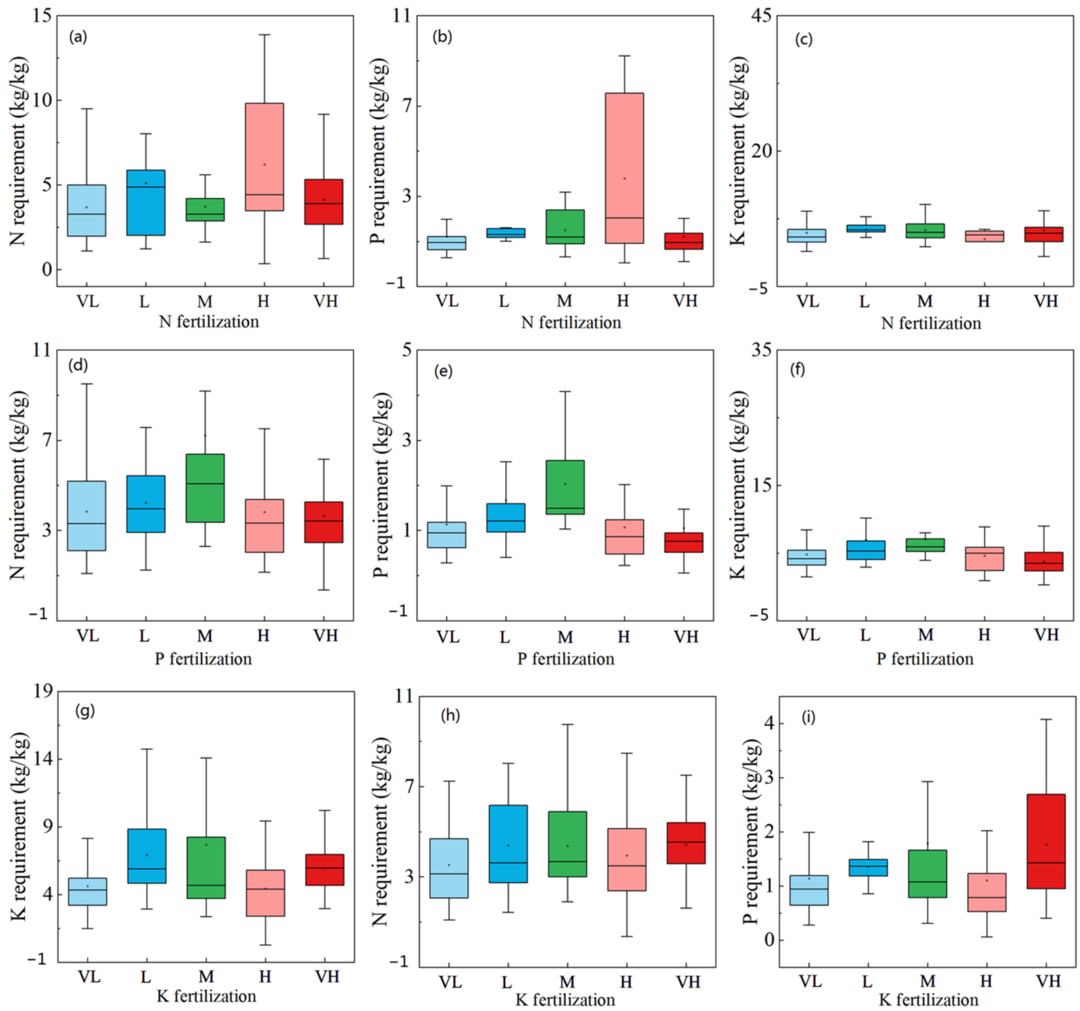

Figure 2. Effects of different amounts of nitrogen (**a**,**d**,**h**), phosphorus (**b**,**e**,**i**), and potassium (**c**,**f**,**g**) on the nutrient requirements of potato. The symbol "•"stands for the mean valueinside the box. The median value is marked with a solid line. VL means very low, L means low, M means medium, H means high, and VH means very high.

The required amount of NPK fertilizer per ton of potato was not changed much with the change in K application amount (Figure 2g,h). The demand for N, P, and K was the highest when the application of K fertilizer exceeded 155 kg ha^{-1} (very high), 75–115 kg ha^{-1} (moderate), and 35–75 kg ha^{-1} (low) at 5.40 kg N kg^{-1}, 1.79 kg P_2O_5 kg^{-1}, and 6.91 kg K_2O kg^{-1}, respectively. It was lowest when the amount of the K fertilizer applied was lower than 35 kg ha^{-1} (very low), 115–155 kg ha^{-1} (high), and lower than 35 kg ha^{-1} (very low), at 3.71 kg N kg^{-1}, 1.10 kg P_2O_5 kg^{-1}, and 4.62 kg K_2O kg^{-1}, respectively.

3.2. Current Status of the Distribution of Potato Yields

Nearly 90% of the area that farmers to potatoes in the survey area was concentrated between 0.1 and 0.7 ha (Figure 3a), 32.4% of the planting area was between 0.1 and 0.3 ha, and 27.4% of the planting area was between 0.3 and 0.5 ha. It was apparent that a small area was planted for potatoes and primarily managed by independent farmers, and there were relatively few cooperatives and companies involved. The varieties planted primarily included Leshu 1, Qingshu 9, Minshu 2, Qingshu 2, Xiazhai 65, etc. (Figure 3b). The varieties that were planted the most included Le Potato No. 1 and Qingyu No. 9. They comprised 31.3% and 17.0%, respectively. Because the planting varieties in the Qinghai counties (cities) were local conventional varieties, there were large regional differences and more varieties. Thus, the survey of varieties should be strengthened, and the scope of the research expanded to be more representative of the Qinghai potato planting varieties.

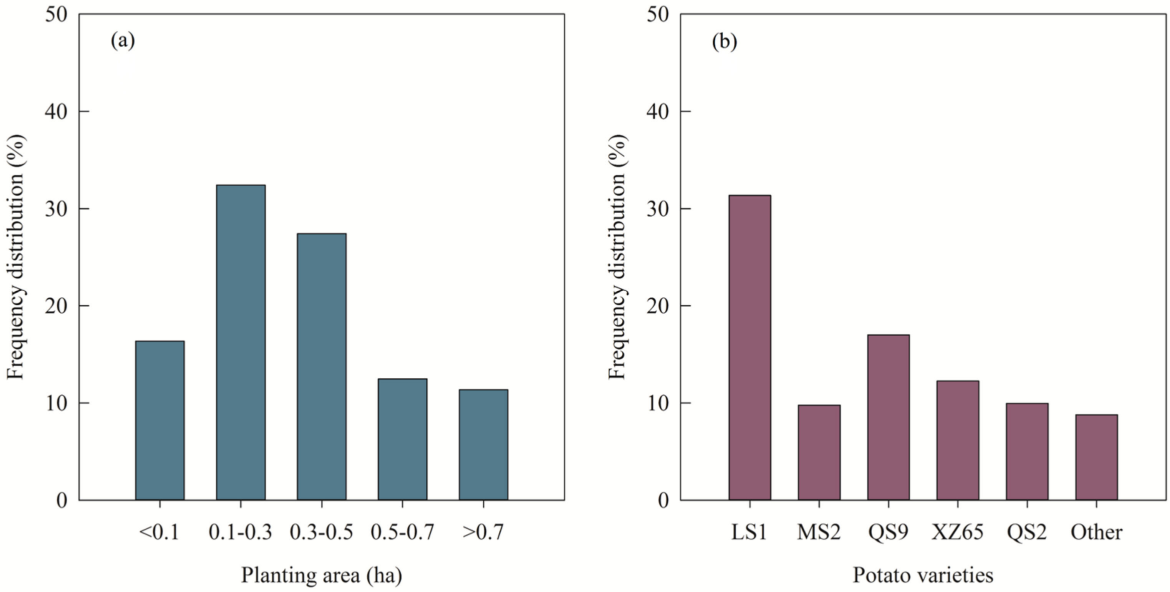

Figure 3. Planting area (**a**) and potato varieties (**b**) in Haidong City.

According to the data on the amount of potatoes sown in Qinghai (Figure S2), the distribution was between 1350 and 3750 kg ha^{-1}. When the yield was higher than average, the average amount was 2290 kg ha^{-1}. If the amount sown was too low or too high, it could not produce a high yield. In the survey, 60.9% of the farmers had sown 2250 kg ha^{-1} of potatoes, which was relatively practical.

Compared with the previous crops (Figure S3), the Qinghai farmers chose potatoes with a higher proportion of rotation crops, accounting for 33.1%, followed by rapeseed (*Brassica napus*) and wheat (*Triticumaestivum*) with 25.7% and 23.7%, respectively, while corn (*Zea mays*), broad beans (*Viciafaba*), soybeans (*Glycine max*), flax (*Linumusitatissimum*), and oats (*Avena sativa*) were rotated less frequently. A comparison of the yield of potatoes under different crop rotation systems revealed that the potatoes had the highest yield when the potatoes were rotated with maize, with an average of 34,274 kg ha^{-1}, followed by

27,890 kg ha^{-1} during continuous potato cropping and 25,904 kg ha^{-1} during broad bean rotation (Figure S3). When the previous crops, wheat and rapeseed, were rotated more frequently, there was a moderate potato yield with 24,044 kg ha^{-1} and 22,984 kg ha^{-1}, respectively. The lowest yield of potato was only 15,900 kg ha^{-1} during its rotation with soybean. The results showed that different rotational crops had a substantial influence on the yield of potatoes. Although the potato that was continuously cropped did not have low yields, this was the result of only one continuous cropping cycle. Thus, the results of long-term continuous cropping merit further study, and the effect of continuous cropping on the soil and potato qualities should also be considered. This study showed that there was a higher yield of potatoes when they were rotated with broad beans and a lower yield when rotated with soybean. This indicated that not all leguminous crop rotations can increase crop yields. This phenomenon could be related to an insufficient number of surveys, but the reasons for this phenomenon merit further study.

Potato yield is divided according to the method of this study, and the results of each yield classification show that <17,760 kg ha^{-1} (very low), 17,760–23,070 kg ha^{-1} (low yield), 23,070–28,380 kg ha^{-1} (middle yield), 28,380–33,690 kg ha^{-1} (high yield), and >33,690 kg ha^{-1} (very high) accounted for 17.5%, 23.8%, 16.1%, 26.0%, and 16.6%, respectively (Figure 4), with a high coefficient of variation of 33.2%.

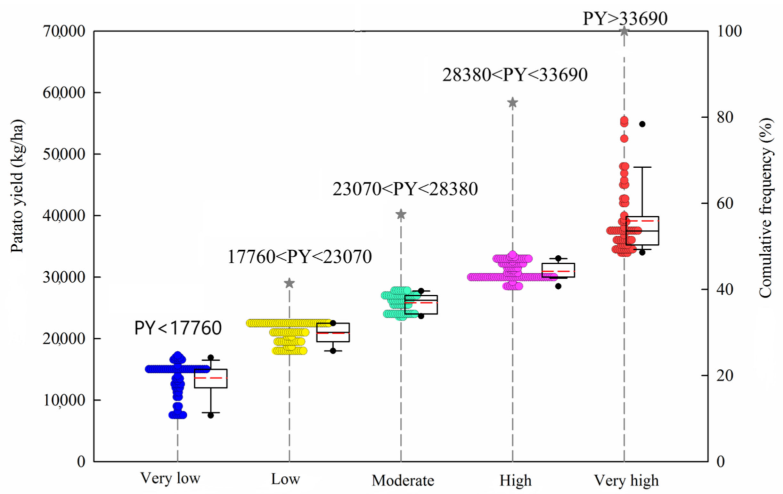

Figure 4. The range of the yield of potatoes in Haidong City.

3.3. Current Situation of Potato Fertilization and Potential Analysis of the Reduction in Amount of Fertilizer

There are two primary types of periods for fertilization for Qinghai potato farmers: autumn (mulch) planting and spring (mulch) planting. Of the farmers who planted in the autumn, 29.6%applied N fertilizer, 26.3% applied Pfertilizer, and merely 13.0% used Kfertilizer. Sources of K primarily included compound fertilizer and organic fertilizer (Table 6). Most of the farmers (69.5%) who planted and mulched with film in the spring applied N (69.5%) and P fertilizer (67.6%), while 35.2% applied K fertilizer. The types of fertilizer primarily included urea, diammonium phosphate, compound fertilizer, and a small amount of farm manure. The results indicated that more farmers applied base fertilizer. According to the proportion of farmers applying topdressing, 24.9% of the farmers topdressed N fertilizer, while only 4.2% and 4.7% of the farmers topdressed P and K fertilizer, respectively. Nearly 80% of the farmers did not apply topdressing and applied fertilizer once, while most of the farmers who applied by topdressing only applied N fertilizer, which was most commonly urea. The farmers who applied P and K fertilizers chose fertilizers such as DPA, compound fertilizer, and foliar fertilizer.

Table 6. Basal topdressing ratio and nutrient sources.

Fertilizer	Application Ratio (%)			Nutrient Source (%)	
	Film Mulching and Planting in Autumn	Film Mulching and Planting in Early Spring	Topdressing	Organic	Inorganic
N	29.6	69.5	24.9	4.8	95.2
P	26.3	67.6	4.2	3.2	96.8
K	13.0	35.2	4.7	27.7	72.3

There was no correlation between the yield of potatoes and the use of N, P, and K (Figure 5). The average amount of N fertilizer applied was 213 kg ha^{-1}, and 95.2% of that originated from chemical fertilizer. Only 4.8% originated from organic fertilizer. The average amount of phosphate fertilizer was 202 kg ha^{-1}, and the nutrients derived from chemical fertilizer comprised 96.8%. The average amount of K fertilizer applied by the farmers was 43 kg ha^{-1}, and 72.3% originated from chemical fertilizer and 27.7% from organic fertilizer. This showed that most potato growers applied chemical fertilizer and strongly preferred it to organic fertilizer, and less K fertilizer was applied. The K for the crops primarily originated from compound fertilizer and organic fertilizer, and this mode of fertilization was irrational.

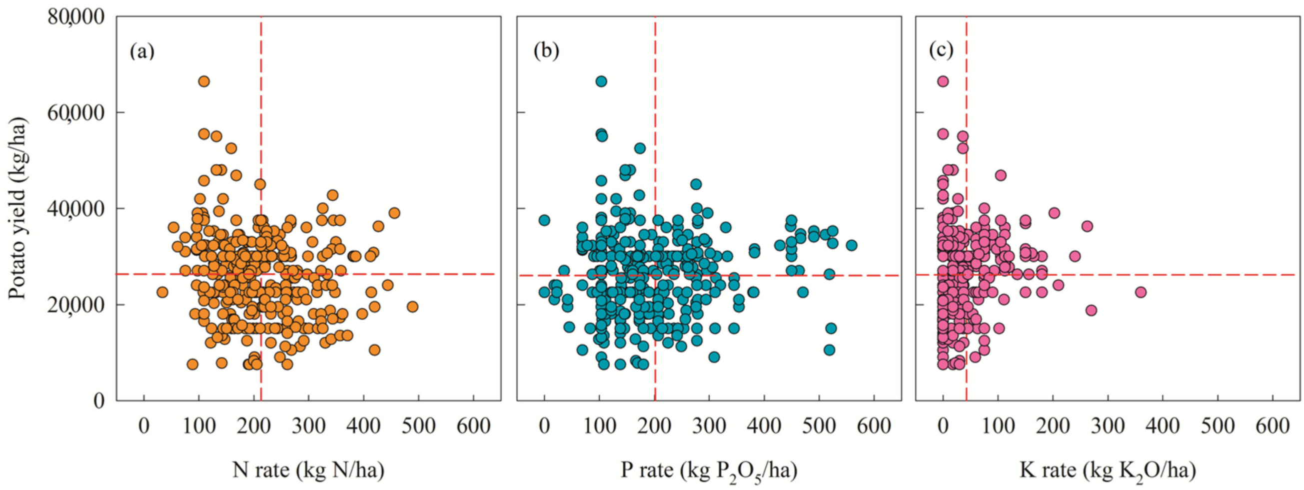

Figure 5. Effects of different application of nitrogen (**a**), phosphorus (**b**), and potassium (**c**) on the yield of potato. Vertical dotted linesare the average amount of N, P_2O_5, and K_2O fertilizer applied, respectively; horizontal dotted linesare the average yield of the potatoes planted by farmers. K, potassium; K_2O, potassium oxide; N, nitrogen, P, phosphorus; P_2O_5, phosphorus pentoxide.

An analysis of the current situation of the application of N fertilizer by farmers who produced different levels of yields of potatoes (Figure S4) showed that, regardless of the yield, there was a low proportion of farmers who applied moderate levels of N fertilizer. Only approximately 15.0% of the respondents reported applying such levels of N fertilizer. Most of the farmers applied higher amounts of N, which were mostly higher than the moderate level. A total of 46.0% of the farmers applied very high amounts of N; 17.5% used high amounts, and more than half of the farmers applied excessive amounts of N. When the level of yield was low to high, the proportion of N fertilizer applied was higher than the average (high + very high), which was 73.0%, 67.4%, 62.1%, 61.7%, and 51.7%, and the proportion gradually decreased. The proportion of farmers with inputs of N below the moderate level gradually increased from 14.3% to 38.3%, while the proportion of farmers who applied N fertilizer at the moderate level did not change much and wasbetween 10.0% and 19.1%. This showed that the rate of N applied was not proportional to the yield, and scientific fertilization is required to obtain high yields.

The results of the application of P fertilizers by farmers (Figure S4) showed that when the level of yield was low to high, the proportion of phosphate fertilizer applied was higher than the average (high + very high) and was 61.6%, 63.8%, 62.1%, 67.0%, and 56.7%. The proportion gradually increased. However, the lowest proportion of P fertilizer was applied when there was a high yield. The proportion of P fertilizer applied that was low (low + very low) was 12.7%, 15.1%, 25.9%, 19.1%, and 18.3%, and the proportion increased first and then decreased with the increase in the level of production.

In contrast to the applications of N and P fertilizer, the proportion of users that applied low levels of K fertilizer (low + very low) decreased with the increase in the level of yield (Figure S4). However, regardless of the level of production, the proportion of farmers who used little K fertilizer exceeded 60%. When the yield was low, the proportion of farmers who applied low levels of K fertilizer reached 85.7%. The proportion of farmers who applied high levels of K (high + very high) increased with the enhancement of the potato yield, and the highest proportion was only 11.7%. When the yield was low and high levels of K fertilizer were not applied, the levels were moderate or low. It is apparent that the amount of potash fertilizer applied was extremely inadequate, and potato farmers should pay special attention to the application of K fertilizer.

3.4. Current Situation of the Fertilization of Potato with N and an Analysis of a Reduction in the Amount of N Fertilization

The Qinghai potato farmers applied an average of 213 kg Nha^{-1}, and the recommended rate of N to apply was 126 kg Nha^{-1}. The use of this recommendation could reduce the applications of N fertilizer by 87 kg Nha^{-1}, which was a range of 41% (Table S2). At different levels of production, the amount and rate of the reduction of N fertilizer decreased with the increase in the level of yield. When the yield was low, the application could be reduced by 71%. However, the application only needed to be reduced by 7% at high yields. It showed that whether it was low or high yields, the applications of N fertilizer needed to be reduced, particularly for low-yield farmers, and high levels of application of N fertilizer were an important reason for the reduction in crop yields. The analysis of different levels of N applied indicated that when very low levels of N were applied, the low-yield farmers should reduce the amount of N fertilizer applied by 41%, and farmers at the other yield levels needed to increase their use of N fertilizer. This increase should improve the level of yield. High-yield farmers increased their use of N fertilizer by the highest amount and reached 99%. When the application of N was low to moderate, only high-yield farmers needed to reduce their level of application by 49% and 15%, respectively. When the amount of N applied was very high, the application of fertilizer needed to be reduced regardless of the level of yield, and the range of reduction was 15–76%. This indicated that farmers who applied low levels of N and those with high yields but who applied low levels of N needed to increase the amount of N fertilizer that they applied, while the other farmers needed to reduce their application of N fertilizer by varying degrees.

3.5. Current Situation of the Fertilization of Potatoes by P and an Analysis of a Reduction in the Amount of P Used

The Qinghai potato farmers applied 202 kg of P_2O_5 ha^{-1} on average, and the recommended amount of P to apply was 35 kg P_2O_5 ha^{-1}. The application of 167 kg P_2O_5 ha^{-1} could be reduced by 82%, which was twice that of the potential reduction in N fertilizer (Table S3). When there were different levels of yield except for the farmers whose yields were in the middle of the range of yields and needed to increase the application of phosphate fertilizer by 24%, the application of other yields of phosphate should be reduced. The target range of reduction was 75–91%. An analysis of different levels of fertilization showed that when very low levels of P fertilizer were applied, the farmers who obtained low yields still needed to reduce their use by 54%, while other farmers who obtained medium and low yields needed to increase the application of P fertilizer by 34% and 14%, respectively. The increase in yields was observed as high as 100% for the farmers who did not apply P fertilizer at high levels of yield. When the application of P fertilizer was low, farmers with medium and high levels of yield needed to apply 3% and 66% more P fertilizer, respectively, and the other farmers should reduce their application to varying degrees. When the amount of P fertilizer applied was moderate, high, and very high, regardless of the yield, it was necessary to reduce the P fertilizer applied by a range of 60–93%. The results showed that the target of increasing the application of P fertilizer was aimed at farmers who applied very low levels of P and had yields above the low level. In contrast, the other farmers needed to reduce their application of P fertilizer.

3.6. Current Situation of the Fertilization of Potatoes by K and an Analysis of a Reduction in the Amount of K Used

Of these three nutrients, potassium is the one that limits potato yields. The current situation of the application of K fertilizer to potatoes was opposite to those of N and P fertilizers. The average rate of application of K by farmers was only 43 kg K_2O ha^{-1};the recommended rate of K application was 182 kg K_2O ha^{-1}, and 139 kg ha^{-1} of K fertilizer was needed, with an increase of 323%. The increase in yield when higher levels of K fertilizer were applied was much greater than when higher levels of N and P fertilizers were applied (Table S4). In terms of different levels of yields, the increase in application was the smallest at moderate yields, with an average of 275%, and the increase was 132 kg K_2O ha^{-1}. In contrast, the largest increase in application was at high yields, with an average of 519% and an increase of 230 kg K_2O ha^{-1}. From the analysis of different levels of fertilization, as the amount of P applied increased, the amplitude of the K fertilizer applied decreased and ranged from 1786% to 51%. It was necessary to lose 7% when a very high amount of K was applied. When very low levels of K fertilizer were applied, the increase in K fertilizer gradually enhanced the yield by increasing it from 973% to 3716%. When very high levels of P fertilizer were applied, with the increase in yield, the farmers should first decrease and then increase the application of K. The amount of K applied to the farmers with moderate yields was the most suitable

4. Discussion

4.1. Requirements for Potato Nutrients and Their Influencing Factors

To scientifically recommend the application of fertilizers, it is necessary to clarify the nutrient requirements per unit yield of crop production. This study analyzed local experimental data and that from previous studies to show that the amounts of N, P, and K required by the potato tubers were 4.85 kg Nt^{-1}, 1.26 kg P_2O_5t^{-1}, and 6.98 kg K_2Ot^{-1}, respectively, and there were large differences between the varieties. In the northern region of China, to produce 1000 kg tuber yield when achieving 80% potential yield, plants required 4.93, 0.74, and 5.35 kg of N, P, and K, respectively [41]. In India, the amount of nutrients needed was estimated to be 0.67, 0.13, and 0.87 kg of N, P, and K to produceone quintal potato tuber [42]. Gao et al. (2011) collected data from China and other countries on the demands of potatoes for nutrients and found that the amount of nutrients required to produce 1000 kg of potato tubers varied substantially [43]. The demand for plants for N differed by more than 5 fold. This analysis showed that 50% of the N demand was distributed within the range of 3.0–6.0 kg, and most of the P demand was in the range of 1.0–1.5 kg. That of the K was between 2.0 and 12.0 kg, and most of the levels applied were distributed between 4.0 and 6.0 kg. It was apparent that the requirements of the potatoes for nutrients in this study were all in the statistical range of Gao et al. (2011) [43], and the values were reliable.

There were many influencing factors in the requirements for nutrients, including the soil pH, OM, year, fertilizer application, yield [43], varieties, and planting areas. Zhang (2011) also identified different influences on the demands for nutrients [44]. This study found that the nutrient requirements of crops changed depending on the amount of fertilizer that was applied. The application of a moderate amount of N resulted in the lowest demand for Nin potatoes, while the demand for crops for N was the highest when a moderate amount of P was applied. In addition, the amount of N, P, and K fertilizer increased within a certain range. The demand for P and Kin potatoes varied in a parabolic form, and when a very high amount of fertilizer was applied, there was also a high demand for P and Kin the crops.

4.2. Evaluation of Potato Fertilization Evaluation and an Analysis of the Potential Reduction of Fertilizer

This study showed that the yields of the farmers ranged from 7500 to 66,429 kg ha^{-1}, with a high coefficient of variation of 33.2%. There was a relatively high proportion of low yield and very low levels, and the ratio of distribution of farmers in other levels of yield was similar. The category that contained the lowest proportion of farmers was that when the moderate yield was the lowest. This indicated that the yields of potatoes in the survey area changed substantially, which was directly related to the planting and management level of the farmers. Thus, there was an uneven level of planting technology used by the farmers, which resulted in a large variation in yield.

The average rates of N, P, and K fertilizers were 213 kg Nha^{-1}, 202 kg P_2O_5 ha^{-1}, and 43 kg K_2O ha^{-1}, and the yield did not correlate with the amount of fertilizer.

Studies have reported that the biomass of potatoes decreases and the yield significantly decreases after continuous cropping [45,46]. This study found that the yield of potatoes during continuous cropping was higher and reached 27,890 kg ha^{-1}, which was different from the results of previous studies [35,36]. The reason could be that the farmers applied a large amount of fertilizer, which resulted in highly fertile soil, and continuous cropping had no significant impact on the yield of potatoes. Other studies reported that after continuous cropping, the content of AP in the soil tended to increase during the years of continuous cropping [45,47]. The fertilization of the farmers in Qinghai was imbalanced, and the increase in the amount of AK in the soil after continuous cropping was compensated by the crop's demand for K. Thus, the yields were high. However, the effects of long-term continuous cropping merits further study.

In this study, the amount of fertilizer was recommended based on the nutrient requirements and yields regardless of environmental nutrient inputs and other losses. The farmers applied an average of 213 kg Nha^{-1} and 202 kg P_2O_5 ha^{-1}, while the recommendations for the amount of fertilizer to apply were126 kg Nha^{-1} and 35 kg P_2O_5 ha^{-1} on average. Compared with the farmers, the applications of N and P could be reduced by 87 kg Nha^{-1} and 167 kg P_2O_5 ha^{-1}, respectively, and the range of fertilization was reduced by 41% and 82%, respectively. The amount of N fertilizer could be reduced by 71% at low yields and by only 7% at high yields. The potato growers could still produce high yields with very low or low rates of fertilization owing to the large number of nutrient residues caused by long-term excessive fertilization and high soil fertility. In the same manner, over-fertilization led to reduced yields, which was also the reason for the low yields despite the large amount of fertilizer applied by the farmers. In addition, the application of phosphate fertilizer by the farmers who had high yields was lower than those of the farmers with low yields, which indicated that the excessive applications of phosphate fertilizer to the potato plants in Qinghai led to a decrease in yield and the amount of P fertilizer should be appropriately reduced.

The primary purpose of fertilization is to supplement the nutrients contained in the crops to maintain soil fertility. However, there was a serious problem of a surplus of N in farmland soil in China, with an average of 74 kg Nha^{-1} [48]. The residues of N in the soil in the dryland farmland on the Loess Plateau increased significantly [49]. In addition, the AP in the soil also increased significantly [50]. This study found that more than 60% of the farmers who planted potatoes in Qinghai applied too much N and P and too little K. The farmers only applied 43 kg K_2Oha^{-1} of K on average and primarily used chemical fertilizers, with less application of organic fertilizers. Although the AK was relatively abundant in the northern soil, the long-term emphasis on N and P fertilizers and the limited amount of K fertilizers applied would also lead to an imbalance in the supply of N and P owing to the depletion of K in the soil [51]. The recommended amount of K was 182 kg K_2O ha^{-1}, and the farmers needed to increase the amount of K fertilizer applied by 139 kg ha^{-1}. This was an increase of 323%. The degree of fertilization of potatoes varies greatly from region to region. More than 50% of farmers in the arid area of Longzhong in the Gansu Province used low levels of N and P fertilizers. More than 70% of the farmers applied very low amounts of K fertilizers, and virtually no organic K fertilizer was applied. The average amounts of fertilizer applied to dryland potatoes in the hilly area of Yinshan Mountain in Inner Mongolia were 102 kg Nha^{-1}, 57.2 kg P_2O_5 ha^{-1}, and 5.9 kg K_2O ha^{-1}. The amount of P applied by the growers was too high and too low, and the amounts of K fertilizer applied were very low. In the mountainous areas of southern Ningxia, the rate of N applied was not synchronized with the yield, and more than 50% of the farmers applied too much N fertilizer and too little phosphate fertilizer. It was apparent that there were significant differences in the application of N and P fertilizers during the cultivation of potatoes. However, too little K fertilizer was applied, and there was even less application of organic fertilizers. Most of the nutrients absorbed by crops originate from chemical fertilizers.

In addition, the criteria for the classification of fertilizer inputs varied, which led to a high degree of variation in the results. Wang (2014) and Zhang (2011) both reported on potato production, but owing to the difference in fertilization grading standards, they reported opposite values on the status of application of N and fertilizer to potato [35,36]. Thus, more reasonable fertilizer applications and a yield division standard should be unified in the same area, which is of practical significance for the long-term monitoring of the status of potato cultivation and to provide scientific recommendations.

5. Conclusions

The required amount of NPK fertilizer per ton of potato was 4.85 kg N, 1.26 kg P_2O_5, and 6.98 kg K_2O, respectively, which was a ratio of 1:0.25:1.44. The amount of fertilization had a substantial impact on the requirements of the crop. The average yield of potatoes from all the farmers in the survey was 26,069 kg ha^{-1}, and the average amount of N, P, and K fertilizers was 213 kg N ha^{-1}, 202 kg $P_2O_5ha^{-1}$, and 43 kg K_2O ha^{-1}, respectively. The yield did not correlate with the amount of fertilizer. More than 60% of the farmers applied too much N and P fertilizer and too little K fertilizer, and the nutrients primarily originated from chemical fertilizers. Less organic fertilizer was applied. According to the yield and nutrient requirements, the recommended rate of N fertilizer applied was 126 kg Nha^{-1} on average, and farmers should reduce their applications of N fertilizer by 41%. The recommended amount of phosphate fertilizer was 35 kg P_2O_5 ha^{-1} on average, and the farmers should reduce their applications of P fertilizer by 82%. The recommended amount of K fertilizer was 182 kg K_2O ha^{-1} on average, and the farmers should increase this by 323%. The analysis of the level of yield and fertilization status of farmers indicated that low-yield farmers should reduce their applications of N and P fertilizers. High-yield farmers should increase the amounts of N and K fertilizers applied and reduce that of P fertilizers when the amount of fertilizer is low or moderate. All the farmers should increase the amount of K fertilizers applied regardless of the yield of potatoes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14030612/s1, Figure S1. Distribution of potatoes in Qinghai Province.XN stands for Xining City, HD for Haidong City, HB for Haibei State, HN1 for Huangnan State, HN2 for Hainan State, GL for Guoluo State, YS for Yushu State, and HX for Haixi State; Figure S2. Seeding rate in Haidong City; Figure S3. Proportion of previous crop and potato yield after rotation in Haidong City; Figure S4. Relationships of potato yield to N, P2O5, and K2O fertilizers; Table S1. Nutrient requirements, yield and amount of fertilizerof the different potato varieties; Table S2. The status of N fertilization by farmers and its recommended rate; Table S3. The status of P fertilization by farmers and its recommended rate; Table S4. The status of K fertilization by farmers and its recommended rate.

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