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Regional-Scale Virtual Nitrogen, Phosphorus, and Potassium Factors of Potato Production in China

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Abstract: Improving yield in potato production with minimal environmental impact is of great significance for China's potato staple food policy. Previous research has been limited by the absence of regional-scale parameters to evaluate the environmental costs of regional potato production. To address this gap, we utilized the input–output analysis method to offer a thorough estimation of nitrogen (N), phosphorus (P), and potassium (K) inputs and outputs in the potato production stage at a regional scale, leveraging a meta-analysis dataset from plenty of the literature. On this basis, we calculated the virtual N, P, and K factors (VNFs, VPFs, and VKFs) for different potato production regions, under both conventional and optimal management practices. China's potato production suffered from excessive N and P inputs, while K inputs remained insufficient. Significant spatial heterogeneities were observed for the VNFs, VPFs, and VKFs across different potato production regions. Northeast China and northwest China emerged as the most suitable potato cultivation regions because they demonstrated high potato yields with relatively low inputs and, consequently, lower VNFs and VPFs. Southwest China was the most vital region where targeted efforts could lead to reducing VNF and VPF, thus significantly mitigating environmental N and P losses. In addition to reducing fertilizer inputs, site-specific and whole optimization measures are proposed to lower the environmental costs and promote the sustainable development of potato production.

Keywords: virtual resource input; environmental effect; virtual factor; potato production; regionalization

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1. Introduction

With the growth of population and improvement of living standards, China is confronting growing challenges in guaranteeing food security and implementing agricultural sustainability simultaneously. Potato (*Solanum tuberosum* L.) is the fourth largest food crop in the world and China, following rice, wheat, and maize, playing a vital role in ensuring food security [1]. Potato is highly nutritious and offers a rich variety of essential nutrients. Its production of food energy and value per unit area surpass those of other staple foods [2]. Since the Chinese government carried out the 'potato-as-staple-food' (PSF) policy in 2015, potato production in China has steadily risen, with a growth of 13.8% from 82.9 million tons in 2015 to 94.4 million tons in 2021, accounting for 25.1% of the world's production in 2021 [3], while the per-unit yield of Chinese potatoes lagged behind the world average, standing at only 78.7% [3]. Controlled by the limited arable land resources in China, enhancing potato yield per unit area becomes critically important. The use of nitrogen (N), phosphorus (P), and potassium (K) fertilizers is crucial for maintaining high potato yields. While excessive fertilization can cause serious environment problems, such as the release of greenhouse gases (GHGs) especially nitrous oxide (N_2O), water eutrophication, fertilizer leaching to groundwater, and soil acidification [4]. Improving crop yields while simultaneously reducing resource inputs and environmental impacts requires comprehensive solutions, which has attracted increasing attention from researchers.

With the rising frequency and amount of food trade among different regions, numerous studies have focused on resource inputs and outputs linked to the production and consumption of food in a given region [1,5,6], or virtual resources' inputs and environmental impacts of food system of a given region, e.g., the trade of N, water, land, and natural resources embodied in food trade [7–9]. Other research has centered on quantifying N and P losses for producing per unit of available N and P in the final consumed food items at their production stages [10,11], as well as assessing the resource use and GHG emissions connected with food trade or waste within a given region from a global perspective [12–15]. Under this context, virtual new N and P factors (VNNF and VNPF) or N and P costs (NC and PC) of food defined as the N or P inputs to the food system from outside for producing per unit available N or P in the final consumed food items at their production stages [10,16], or virtual N factor (VNF) of food defined as the N losses to the environment associated with per unit available N in the final consumed food items in the food production-to-consumption chain [11,17,18] were widely developed in the world. These factors can be used to track virtual new N and P inputs or virtual N losses to the environment during the final food consumption by households at personal, regional, or national scale, and to evaluate the resource demands and environmental effects of a given region in relation to its surrounding areas or the origin of imported foods [11,16]. Hence, regional scale parameters are significant in evaluating virtual resource inputs or outputs and environmental effects embodied in food production and trade.

National-scale indicators such as VNNF, VNF, NC, and PC for different food items in China have been estimated in a series of studies [5,10,17,19]. These indicators serve as parameters for evaluating the virtual new N/P inputs to food systems and the environmental effects of final food consumption by households on surrounding areas at urban and provincial scale, given the lack of provincial and regional scale parameters [16,20]. Nevertheless, owing to the diverse soil–climate conditions and management practices prevalent in different regions, the above indicators exhibit measurable differences for each food item across different agricultural regions in China; magnitude differences exist even within the same region and among different regions for a particular crop [19,21,22]. As for potato—a newly promoted staple food in recent years—there is a scarcity of data for the comparisons of the virtual environmental effects (e.g., VNF, VPF—the virtual P factor, and VKF—the virtual K factor) of per unit N, P, and K from supplied potato out of farm gate for food consumption by households at the regional scale. These parameters hold great significance for agronomists and policymakers to make decisions on improving potato production efficiency and achieving sustainable development in China's potato production from regional optimization perspectives.

This study aimed to (i) analyze the virtual total N, P, and K inputs, outputs, and surpluses of the potato production system from chemical fertilizers, manures, seeds, straw, atmospheric deposition, irrigation, biological N_2 fixation (BNF), and pesticides in different potato production regions, through a meta-analysis dataset from the published literature spanning from 2000 to 2020; (ii) calculate the VNFs, VPFs, and VKFs as well as their regional losses of different potato production regions, from the conventional and optimal management practices; and (iii) examine the correlations among nutrient surpluses, virtual total inputs, main input indicators, and virtual emission factors. The findings of this research could provide regional-scale parameters for the virtual resource inputs/outputs and environmental effects, enrich modeling studies associated with potato food trade, and would be helpful for formulating measures to improve potato production with fewer resource inputs and lower environmental costs from regional optimization perspectives under the background of China's PSF policy.

2. Materials and Methods

2.1. Description of the Regions and Study Boundary

China is the largest potato-cultivating country with the highest yield in the world. As potato has strong adaptability to different environmental conditions (e.g., climate, altitude, and latitude), it is widely grown across different agricultural regions in China [6,23]. According to the climatic zone and topographic zone, we divided the potato-producing areas into six regions: Northeast China (NEC), North China (NC), Northwest China (NWC), Central and East China (CEC), Southwest China (SWC), and Southeast China (SEC). Hong Kong, Macau, and Taiwan were not contained due to data unavailability. The detailed provinces and municipalities of each region were stated in a previous study [6]. In 2020, NEC, NC, NWC, CEC, SWC, and SEC accounted for 3.3%, 6.8%, 29.0%, 7.7%, 49.9%, and 3.3% of the national potato sown area, respectively [24].

From the perspective of the life cycle and input–output analyses, we set the study boundary as the virtual N, P, and K flows among the crop, the pedosphere, and the atmosphere from potato cultivation to the harvest period, as illustrated in Figure 1. The virtual total N, P, and K inputs encompass external inputs imported into the crop-producing system and internal inputs from recycled materials [10]. The external inputs, termed virtual new N, P, and K inputs in our previous research [1,6], consisted of N, P, and K derived from chemical fertilizers, irrigation water, atmospheric deposition, BNF (solely an N source), and pesticides (solely a P source). The internal inputs, also called recycled inputs, encompassed N, P, and K from manures, straws returning to the field, and potato seeds. The virtual total N, P, and K outputs covered three parts: (1) N, P, and K uptakes by the entire potato crop, containing potato tubers, aboveground stems and leaves, and underground roots; (2) N, P, and K losses to the pedosphere through leaching, erosion, runoff, and accumulation in the topsoil; (3) N emissions to the atmosphere, including N_2O emissions, ammonia (NH_3) volatilization, and denitrification. The VNF of potato was defined as the total amount of reactive N (Nr) losses to the environment for producing per unit of available N in potato for consumption. We neglected the virtual N release from additional energy consumption during potato production due to a lack of available information. Based on the aforementioned input–output analysis, we calculated the VNFs of potatoes for each of the six production regions. Similarly, the VPF and VKF were computed using the same concept, and this framework could be copied to other food items as well. The potato production management practices were categorized into conventional practices and optimized practices. Conventional practices mainly aimed to achieve high yield by using substantial amounts of fertilizers and irrigation water according to local farmers' experiences. Optimized practices referred to the knowledge-based practices, which managed potato production by either applying moderate fertilizer amounts, optimizing irrigation management, or optimizing cultivation modes [6].

2.2. Data Collection

The data of N, P, and K input amounts from chemical fertilizers, irrigation water, atmospheric deposition, BNF, and pesticides per unit area, as well as the yields per unit area and commodity ratios of potatoes in the six potato-producing regions under both conventional and optimal practices, have been previously accounted for in our earlier research [1,6] and were shown in the Supplementary Materials (Table S1). This paper supplemented the data regarding the recycled inputs from manures, potato straws, and potato seeds under the two management practices of potato planting. The data on regional usages of manures and potato seeds were collected from the copious published literature in the ISI-Web of Science and China National Knowledge Internet (CNKI) databases, focusing on potato planting experiments in China during 2000–2020. The data collection criterion was that at least one of the above data was reported for an entire potato growing season under field conditions. A total of 303 observed results about manure types and usages for potato growing were identified (Table S2), encompassing 20 items in NEC, 31 items in NC, 97 items in NWC, 62 items in CEC, 58 items in SWC, and 35 items in SEC. As manures are usually applied as auxiliary fertilizers in combination with chemical fertilizers, limited research has been conducted specifically on determining the optimal amounts of manures. So, the calculated average values of manures in the six regions were used as the application amounts for both conventional and optimized modes. The per unit area N, P, and K usages of manures were calculated by multiplying the usages of manures with their respective N, P, and K contents, which were sourced from literature or books (Table S4). The seed amounts per unit area (Table S3) and N, P, and K contents of potato seed (Table S5) were also directly collected or calculated using the per seed weight multiplied by the potato density. We gathered a total of 286 data items regarding potato seed amounts, containing 19 items in NEC, 29 items in NC, 83 items in NWC, 61 items in CEC, 57 items in SWC, and 37 items in SEC.

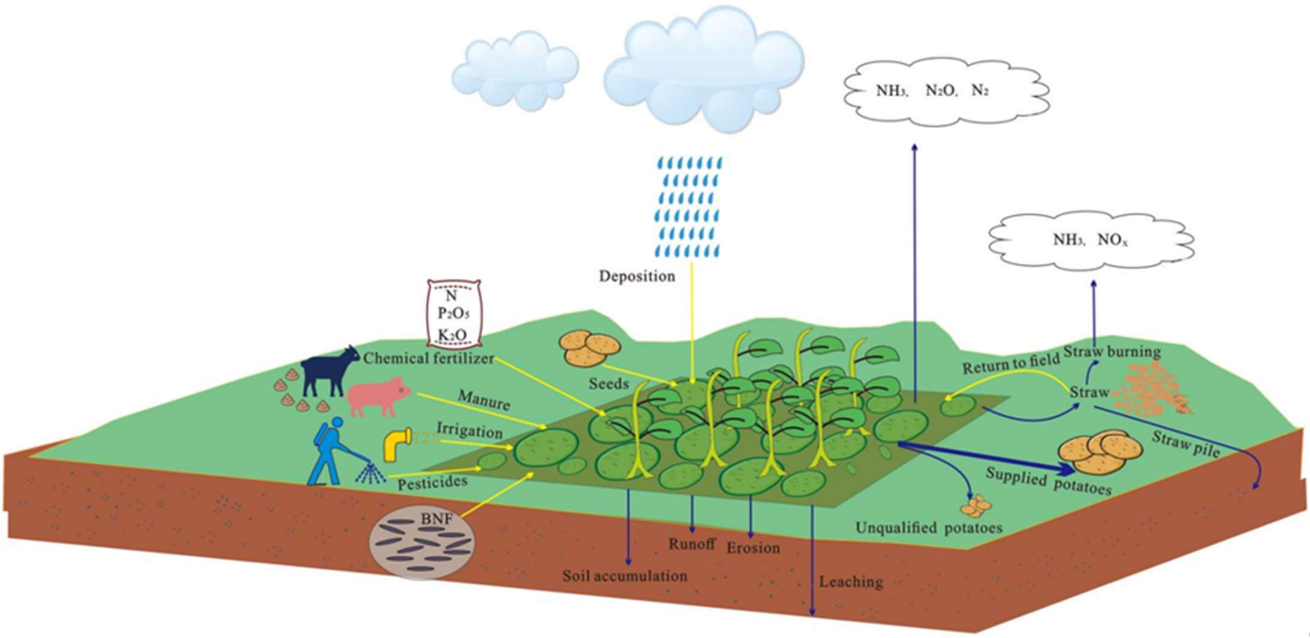

Figure 1. The theoretical model and calculation boundary of this study. Yellow arrow indicates the input pathway; blue arrow indicates the output pathway.

The BNF rate was assumed as 18.8 kg N ha^{-1} [17]. The contents of N, P, and K in irrigation water, as well as the N, P, and K deposition amounts from the atmosphere, were directly collected from the published literature (Tables S6–S8). N, P, and K inputs of irrigation water were calculated by multiplying the collected data on irrigation amounts in different potato production regions with the concentrations of N, P, and K in irrigation water (Table S6). In the calculation of P embodied in pesticides, it was assumed that half of the pesticide content contained P, and the mean P concentration in pesticides was set at 5% [25]. The nutrient uptake rates by crop for producing 1 Mg (=10^6 g) of potatoes were collected from the different literature across China (Table S9), and these data were then used for calculating the N, P, and K uptake amounts by the entire potato crop. N_2O emission factors in the upland were set as 1.1% from chemical N fertilizer [26] and 0.6% from manure N [27] in China as a whole, as there was a lack of research about N_2O emission factors of regional upland fields (Table S10). Regional NH_3 volatilization factors from chemical fertilizer and manure in the upland were collected from the literature shown in Table S11. The N and P emission factors via runoff, erosion, leaching, and denitrification in the six potato production regions were calculated as the mean values of different provinces within each production region, based on data from Ma et al. [10] (Table S12). K loss in upland is primarily attributed to leaching [28]. Due to limited research on K leaching rates in different regions of uplands, we set the K leaching rates of upland at 2% in northern China [29] and 6.7% in southern China of the external input K amount [30]. The typical uses of potato straws include feeding animals (56%), returning to the field (18.7%), burning as fuel (6.6%), and piling aside as waste (18.7%) [31]. When returned to field as organic matter, potato straws contribute to the cropland soil by adding carbon (C), N, P, and K, while also motivating soil emissions of N_2O and NH_3, similar to the effects of manures. When burned as fuel, the N in straws will be transformed into nitrogen oxides and released to the atmosphere. When piled aside as waste, the N, P, and K in straws become a burden to the soil and nearby water body. Thereby, returning to field, burning, and piling as waste of potato straws were taken into account as resource losses to the environment.

2.3. Data Calculation

According to the aforesaid definitions, we first calculated the inputs and outputs of produced potatoes, then calculated the VNF, VPF, and VKF of potatoes available for consumption. Equations (1) to (10) were used to calculate these indicators:

$$VN_{In} = N_{Fertilizer} + N_{Manure} + N_{Straw\ returning} + N_{Irrigation} + N_{Deposition} + N_{Seed} + N_{BNF} \quad (1)$$

$$VP_{In} = P_{Fertilizer} + P_{Manure} + P_{Straw\ returning} + P_{Irrigation} + P_{Deposition} + P_{Seed} + P_{Pesticide} \quad (2)$$

$$VK_{In} = K_{Fertilizer} + K_{Manure} + K_{Straw\ returning} + K_{Irrigation} + K_{Deposition} + K_{Seed} \quad (3)$$

$$VN_{Out} = N_{Uptake} + N_{Soil\ accumulation} + N_{N_2O\ emission} + N_{NH_3\ volatilization} + N_{Denitrification} + N_{Runoff} + N_{Leaching} + N_{Erosion} \quad (4)$$

$$VP_{Out} = P_{Uptake} + P_{Soil\ accumulation} + P_{Runoff} + P_{Leaching} + N_{Erosion} \quad (5)$$

$$VK_{Out} = K_{Uptake} + K_{Soil\ accumulation} + K_{Leaching} \quad (6)$$

$$N/P/K_{Surplus} = VN/VP/VK_{In} - N/P/K_{Uptake} \quad (7)$$

$$VNF = (N_{N_2O\ emission} + N_{NH_3\ volatilization} + N_{Runoff} + N_{Leaching} + N_{Erosion} + N_{Straw\ burning} + N_{Straw\ pile\ set})/(Y \times N_{Potato} \times R) \quad (8)$$

$$VPF = \left(P_{Runoff} + P_{Leaching} + P_{Erosion} + P_{Straw\ pile\ set}\right)/(Y \times P_{Potato} \times R) \quad (9)$$

$$VKF = \left(K_{Leaching} + K_{Straw\ pile\ set}\right)/(Y \times K_{Potato} \times R) \quad (10)$$

where

VN_{In}/VN_{Out}: virtual input/output N for producing per unit area potatoes, kg N ha^{-1};
VP_{In}/VP_{Out}: virtual input/output P for producing per unit area potatoes, kg P_2O_5 ha^{-1};
VK_{In}/VK_{Out}: virtual input/output K for producing per unit area potatoes, kg K_2O ha^{-1};
$N/P/K_{Surplus}$: N/P/K surplus of per unit area potatoes, kg $N/P_2O_5/K_2O$ ha^{-1};
$N/P/K_{Uptake}$: N/P/K uptake by per unit area of potatoes, kg $N/P_2O_5/K_2O$ ha^{-1};
VNF/VPF/VKF: reactive N/P/K loss to the environment for producing per unit N/P/K in potato available for consumption, kg N kg^{-1} N/kg P_2O_5 kg^{-1} P_2O_5/kg K_2O kg^{-1} K_2O;
BNF: biological N_2 fixation;
Y: potato yield per unit area, kg ha^{-1};
R: potato commodity ratio, %;
$N/P/K_{potato}$: N/P/K contents in potato tuber, set as 0.30%, 0.14%, and 0.50% (Table S5).

Furthermore, we calculated the regional total virtual N, P, and K losses by Equations (11)–(13):

$$VN\ loss = VNF \times Y_T \times N_{Potato} \times R \quad (11)$$

$$VP\ loss = VPF \times Y_T \times P_{Potato} \times R \quad (12)$$

$$VK\ loss = VKF \times Y_T \times K_{Potato} \times R \quad (13)$$

where VN, VP, and VK loss referred to the virtual N, P, and K loss of each potato production region; Y_T referred to the total potato yield in each potato production region.

2.4. Uncertainty and Statistical Analysis

In order to minimize the uncertainties associated with different indicators, we strived to use relevant parameters reported in the literature specific to regional situations whenever possible for calculating the inputs and outputs of N, P, and K. Additionally, we set up uniform criteria for data collection to ensure consistency. The mean values and stand errors (SEs) of different manure application amounts, per seed weights and seed amounts of potatoes per unit area in different regions were calculated with a 90th confidence interval (Tables S2 and S3). The uncertainty of each indicator was calculated by dividing its standard deviation (SD) by its mean value. The mean values and SEs of other N, P, and K inputs, as well as potato yields, were derived from our previous research, as mentioned above [1,6]. For calculating the VN_{out}, VP_{out}, VK_{out}, VNF, VPF, and VKF, etc., because of the complex parameters as cited in Tables S5–S12, if the uncertainties of collected parameters were not directly reported in the literature, such as N/P/K contents of potato tuber, N and P deposition amounts, and N_2O emission factors, we assumed their uncertainties in results were within a range of ~10%–20% [32]. The uncertainty analysis was executed by using the error propagation equation of mathematical statistics [6]. The means and variation ranges resulting from this analysis were presented in the associated contents, supplementary tables, and figures.

SigmaPlot 14.0 software (Inpixon, Palo Alto, CA, USA) was adopted to draw statistical analysis graphs of the study results. OriginPro 2023 software (OriginLab, Northampton, MA, USA) was used for executing Pearson's correlation analysis to check the correlation strength between different factors [33]. The regionalization map of China was created with ArcGIS 10.3 software (ESRI Inc., Redlands, CA, USA).

3. Results and Discussion

3.1. N, P, and K Balances in the Six Potato Production Regions

The thorough analysis of resource balances in crop–soil–atmosphere could provide support data for further assessing their environmental impacts and managing their use efficiencies. The balances of N, P, and K in various potato-sown regions across China are shown in Figure 2. Virtual N and P inputs varied obviously among different regions. Under local conventional planting measures, virtual N inputs varied from the lowest 221.5 ± 69.1 kg N ha^{-1} in NEC to the highest 313.6 ± 91.5 kg N ha^{-1} in NC, in which 65.6–73.0% (149.5–217.2 kg N ha^{-1}) was from chemical fertilizers and 9.8–15.8% (23.0–42.0 kg N ha^{-1}) originated from manures (Figure 2a). The virtual N input amounts for the other four regions distributed as (unit: kg N ha^{-1}) NWC (246.3 ± 66.8) < SWC (273.2 ± 78.8) < CEC (295.9 ± 94.4) < SEC (297.6 ± 62.9). The Chinese national average total N input was 274.7 ± 191.4 kg N ha^{-1}, with 81.9% (224.8 kg N ha^{-1}) attributed to chemical N fertilizer and manure N, which obviously exceeded the total fertilizer N used for roots/tubers in the USA (171 kg N ha^{-1}) and EU (100 kg N ha^{-1}) [1]. Under optimized practices, the virtual N inputs were apparently reduced (Figure 2b), ranging from 214.1 ± 56.5 kg N ha^{-1} in NEC to 288.5 ± 61.7 kg N ha^{-1} in SEC. The reduction rates of N inputs reached 3.3%, 12.7%, 0.5%, 9.0%, 1.7%, and 3.0% in NEC, NC, NWC, CEC, SWC, and SEC, respectively. NC and CEC had relatively larger N reduction potential, with their chemical N inputs reduced by 18.5% and 13.2% with optimal management. Xu et al. illustrated that chemical fertilizer N inputs for potatoes with optimal treatment could reach an average of 164.2 kg N ha^{-1} in China, ranging from 114.2 kg N ha^{-1} in CEC to 215.9 kg N ha^{-1} in SEC [22]. Their results aligned with ours and showed a larger potential for reducing N inputs in partial potato-producing regions, especially CEC, where more than half of the chemical N input could be reduced by optimizing N management.

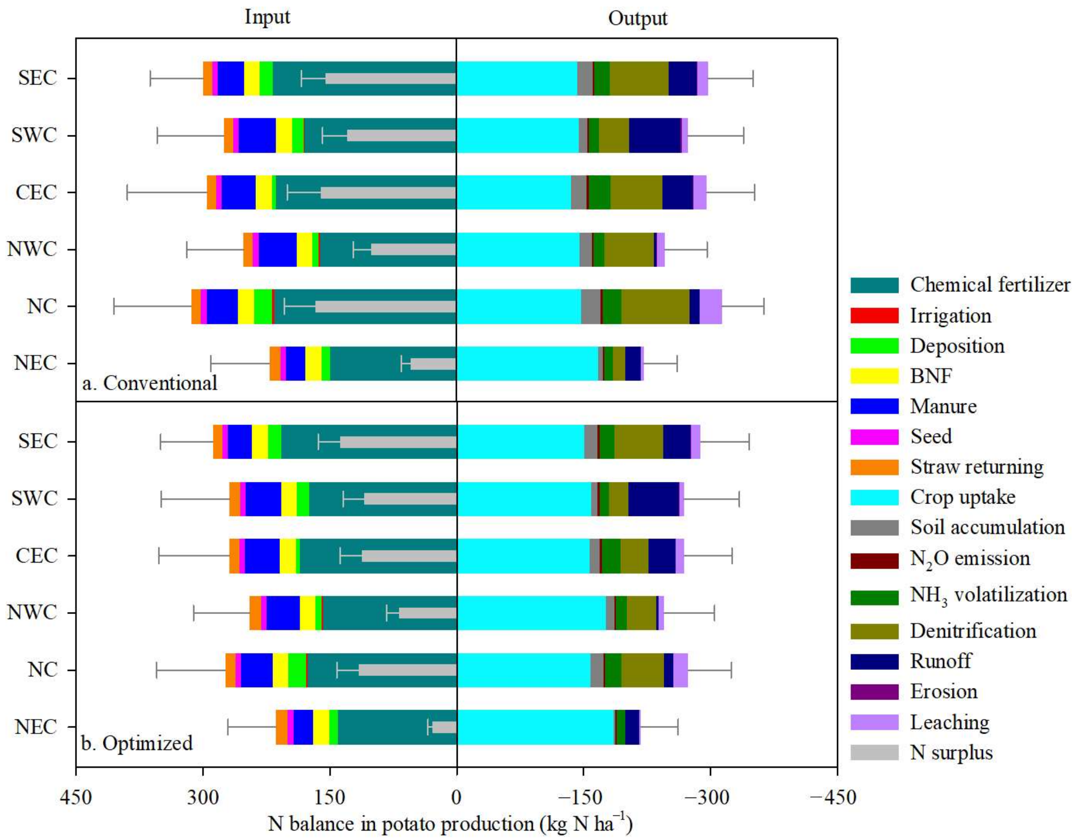

Figure 2. N inputs from different sources and their outputs under conventional (**a**) and optimized (**b**) measures, respectively, in the six potato-sown regions. Error bars represented the standard deviations (SDs).

The overuse of N caused substantial N surplus, ranked as (unit: kg N ha^{-1}): NEC (54.5 ± 11.1) < NWC (100.8 ± 21.2) < SWC (129.1 ± 29.4) < SEC (155.4 ± 28.3) < CEC (160.6 ± 39.9) < NC (166.6 ± 37.2) (Figure 2a). Generally, there was a higher N surplus in southern China than in northern China. Some studies indicated that N losses to the environment, e.g., N_2O emissions, leaching, and runoff, would significantly increase when surplus N exceeded 50.0 kg N ha^{-1} [34,35]. Seen from Pearson's correlation analysis of N surplus, N inputs, and N losses (Figure 3a), N surplus had positive correlations with the virtual input N, chemical fertilizer N, N_2O emissions, NH_3 volatilization, and leaching N loss, and a negative correlation with potato yield. This suggested that higher N surplus leads to greater N losses to the environment in different potato production regions. Moreover, relatively high ambient temperatures and frequent precipitation in southern China like SEC, and CEC favored N losses [36]. The N losses during potato production, including N_2O emissions, NH_3 volatilization, denitrification, runoff, erosion, and leaching, ranged as a sequence of NEC (47.7 ± 11.0, unit: kg N ha^{-1}) < NWC (84.9 ± 10.4) < SWC (117.7 ± 39.7) < SEC (136.0 ± 18.2) < CEC (140.8 ± 24.5) < NC (142.3 ± 15.1), which was consistent with the regional variation trend of N surplus. By optimizing N management, N surplus could be reduced to 29.0–138.0 kg N ha^{-1} among different potato-producing regions, with reduction rates of 46.8%, 30.2%, 31.8%, 30.2%, 15.3%, and 11.1% in NEC, NC, NWC, CEC, SWC, and SEC, respectively. Significant potential exists to cut down N inputs for potato production in certain agricultural regions, particularly in NC and CEC.

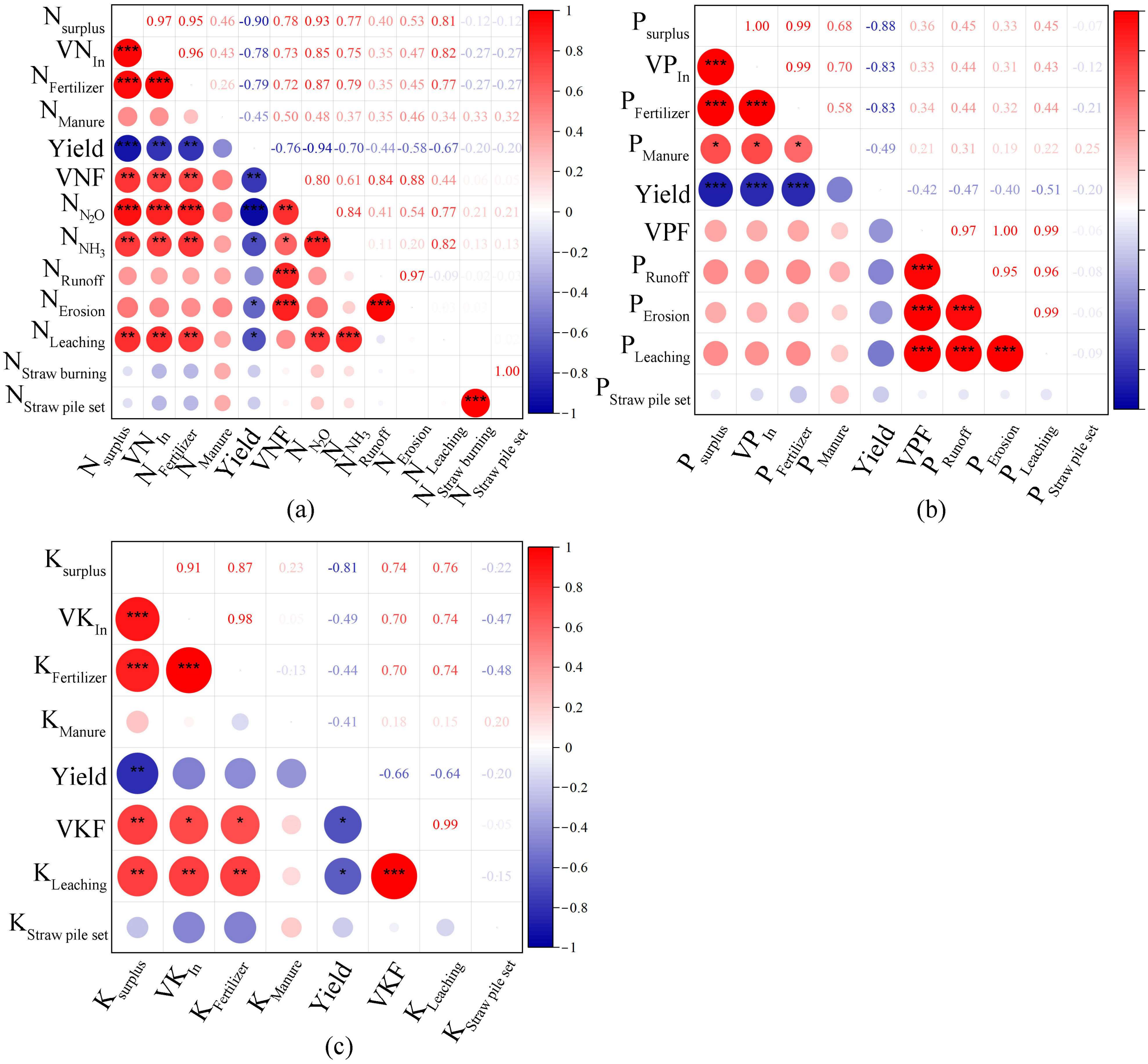

Figure 3. Pearson's correlation coefficients of N surplus (**a**), P surplus (**b**), and K surplus (**c**) with their respective main input indicators and virtual emission factors. Note:* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$.

The virtual P inputs exhibited similar regional distribution characteristics to N inputs under customary farming measures, ranging from 108.0 ± 49.2 kg P_2O_5 ha^{-1} in NEC to 182.1 ± 85.5 kg P_2O_5 ha^{-1} in CEC (Figure 4a). In this scenario, 81.2–87.7% (or 87.6–149.8 kg P_2O_5 ha^{-1}) of total P inputs came from chemical fertilizers and 9.3–12.1% (or 10–22 kg P_2O_5 ha^{-1}) from manures. The total P inputs experienced partial reduction under optimized practices, with reduction rates of 4.5%, 11.0%, 3.7%, 12.6%, 0.9%, and 7.0% for NEC, NC, NWC, CEC, SWC, and SEC, respectively (Figure 4b). A large drop in P inputs took place in NC, CEC, and SEC. The chemical fertilizer P inputs were 128.5 ± 25.0 kg P_2O_5 ha^{-1} under conventional practices and 117.7 ± 19.7 kg P_2O_5 ha^{-1} under optimized practices in China as a whole; these values were around the range of 103–124 kg P_2O_5 ha^{-1} in Lethbridge, Canada and the USA [37,38]. These values, however, were significantly higher than 85 kg P_2O_5 ha^{-1} for potato's chemical P fertilizer inputs in the EU [39]. Xu et al. analyzed that the optimized fertilizer P inputs for potatoes varied from 70.1 kg P_2O_5 ha^{-1} in CEC to 118.6 kg P_2O_5 ha^{-1} in NE [22]. Total P inputs were 1.9–4.0 times the potato crop's P demands in the six potato-sown regions. High P inputs were also observed in three main staple crops—rice, wheat, and maize—in China [40], as well as in the world [41,42], mainly due to the low availability of soil P caused by fertilizer types, soil conditions, and crops.

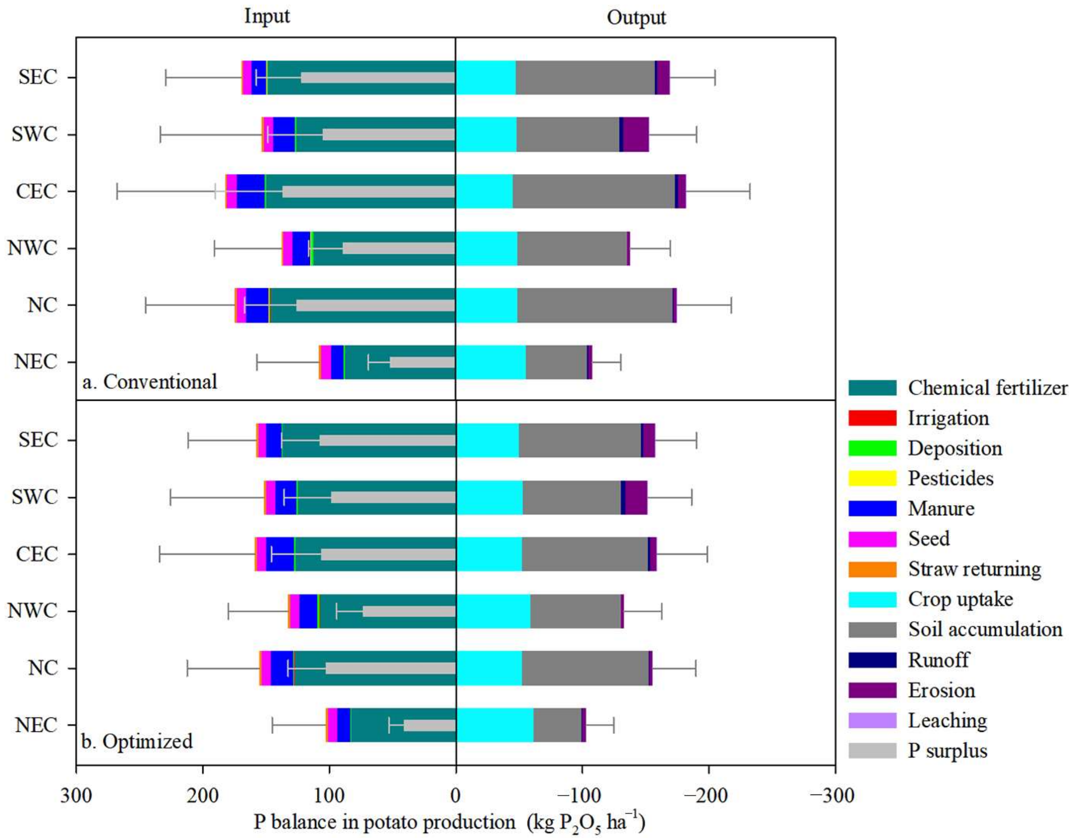

Figure 4. P inputs from different sources and their fates under conventional (**a**) and optimized (**b**) measures respectively in the six potato-sown regions.

The high P inputs also resulted in large amounts of P surpluses, ranging from 52.3 ± 16.7 kg P_2O_5 ha^{-1} in NEC to 137.1 ± 52.9 kg P_2O_5 ha^{-1} in CEC. Yet P losses to the environment through runoff, erosion, and leaching were relatively low, varying from 2.5 ± 1.6 kg P_2O_5 ha^{-1} in NWC to 24.1 ± 13.1 kg P_2O_5 ha^{-1} in SWC. This was attributed to the comparatively lower levels of P runoff (0.13–3.4 kg P_2O_5 ha^{-1}), erosion (2.2–9.5 kg P_2O_5 ha^{-1} except for 19.7 kg P_2O_5 ha^{-1} in SWC), and leaching losses (0.2–1.0 kg P_2O_5 ha^{-1}) in the six regions than those of N. The high P surplus and low P loss to the environment resulted in significant soil P accumulation, ranging from 48.2 ± 14.3 kg P_2O_5 ha^{-1} in NEC to 128.4 ± 46.7 kg P_2O_5 ha^{-1} in CEC. This accumulation contributed to the evident increase in soil P level or the presence of high "legacy" soil P in most of China's croplands [43]. Our findings highlight the substantial potential for reducing fertilizer P input in China's potato production, especially in NC, CEC, SWC, and SEC, if the P use efficiency (PUE) could be enhanced by improving the utilization of the large reserves of residual P present in soils, which have accumulated from previous excessive applications of inorganic fertilizers, animal manure, and other sources [42,44].

The virtual K inputs showed greater variation compared to the virtual N and P inputs, ranging from 165.3 ± 89.4 kg K_2O ha^{-1} in NWC to 286.8 ± 102.2 kg K_2O ha^{-1} in SEC (Figure 5a) under conventional planting practices, in which 63.8–82.6% (or 105.5–237.0 kg K_2O ha^{-1}) were from chemical fertilizers and 8.7–16.9% (or 20.0–36.0 kg K_2O ha^{-1}) from manures. Chinese national average virtual K input was 227.9 kg K_2O ha^{-1} under conventional measures, with 75.1% (or 181.9 kg K_2O ha^{-1}) of it attributed to chemical fertilizer K, which was a bit higher than 137–154 kg K_2O ha^{-1} in Iran and the USA [3,38,45], while significantly higher than the 83 kg K_2O ha^{-1} used for potatoes in the EU [3,38]. Under optimized management, the fertilizer K input for China as a whole was 199.2 kg K_2O ha^{-1}, varying from 138.5 kg K_2O ha^{-1} in NWC to 253.4 kg k_2O ha^{-1} in SEC. The results were in accordance with Xu et al.'s analysis, which reported fertilizer K inputs for potatoes ranging from 137.5 kg K_2O ha^{-1} in NWC to 273.0 kg K_2O ha^{-1} in SEC under optimized management [22]. Yet, the calculated actual K uptakes by potato crop fell within a range from 228.1 ± 86.4 kg K_2O ha^{-1} in SEC to 312.2 ± 61.6 kg K_2O ha^{-1} in NEC under optimized management, indicating that K inputs were inadequate in most potato sown regions except for SEC, and potatoes were absorbing extra needed K from the field soils. Potatoes have higher K requirements than many other crops [46]. K removed from soils by harvested potatoes should be replenished to avoid a decrease in soil fertility. Therefore, K inputs should be increased by at least 44.8%, 17.8%, 71.8%, 5.1%, and 10.1% in NEC, NC, NWC, CEC, and SWC, respectively. A study indicated that potato aboveground K uptake was 57.3% higher than the total K input from chemical fertilizer, manure, seed, irrigation, and atmospheric deposition in Yunnan Province [47]. Additionally, more than one-third of farmlands were found to be insufficient in K input for potato cultivation in Shaanxi Province, northwest China [48]. On the other hand, the mean K inputs should be reduced by 6.3%, 13.8%, and 16.4% in NC, CEC, and SEC, respectively, compared to current customary farmers' practices. A recent survey study has reported that the mean chemical fertilizer K and manure K inputs for potatoes in Guangdong Province had reached 430 and 73 kg K_2O ha^{-1}, respectively, more than 80% of the survey samples had high K input (>350 kg K_2O ha^{-1}) [49]. That is the reason for the obvious increase in soil exchangeable K content in South China [50].

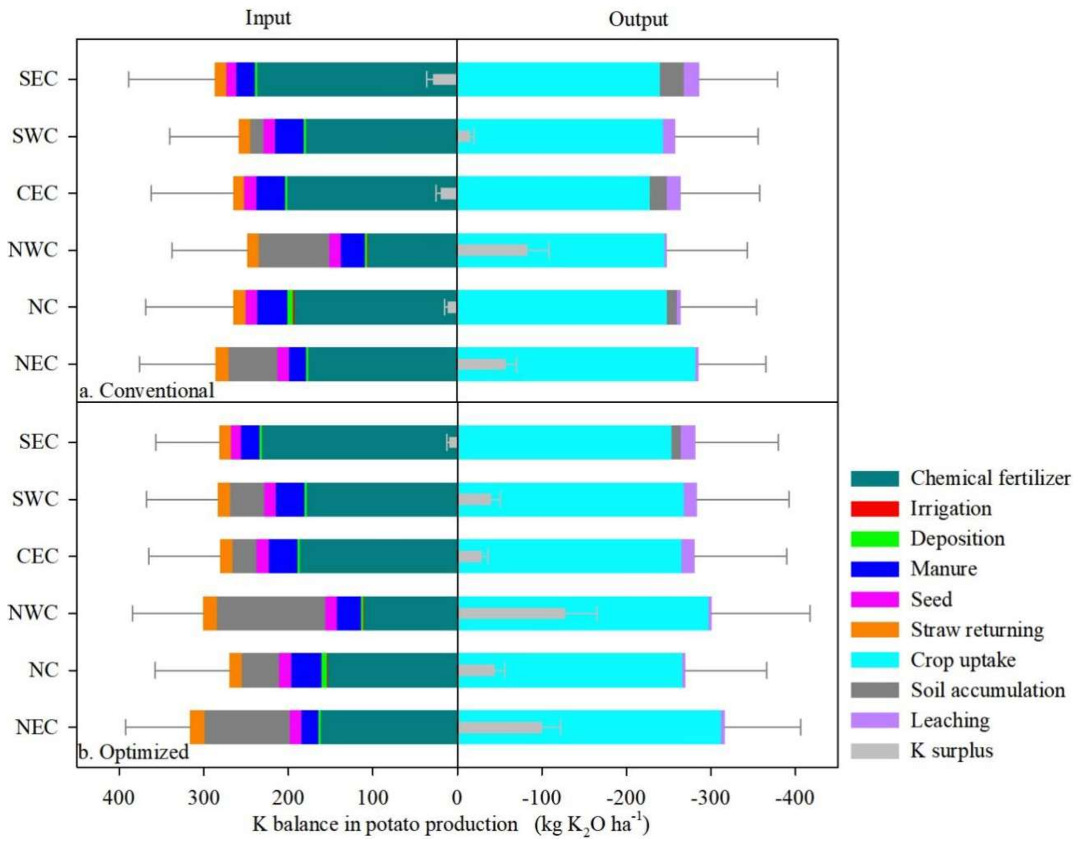

Figure 5. K inputs from different sources and their fates under conventional (**a**) and optimized (**b**) measures, respectively, in the six potato-sown regions. Error bars represented the standard deviations.

3.2. The VNFs of Potatoes in the Six Production Regions

The VNFs of potatoes also represented considerable variations as the N balances cross the six potato cultivation regions. Under conventional management measures (Figure 6a), the VNFs were in the range of 0.63 ± 0.16–1.49 ± 0.47 kg N kg^{-1} N in supplied potatoes (omitted unit in the following text), with a rank of NWC (0.64 ± 0.18) ≈ NEC (0.65 ± 0.16) < NC (1.08 ± 0.25) < SEC (1.12 ± 0.31) < SWC (1.41 ± 0.67) < CEC (1.52 ± 0.49). Chinese national average VNF was 1.07 ± 0.95, which was close to the mean N loss of 1.0 kg N per capita N in root crops during the production stage in China as a whole, as reported by Guo et al. [17]. The VNFs for starchy roots at the consumption end were 1.1 and 1.5 N released kg^{-1} N in consumed potato products in Europe and the USA [11,51]. According to the findings of Spang et al. [52], the supply-to-consumption ratio of roots/tubers was calculated to be 1.28 in mid-/high-income regions. Here, we recalculated VNFs from the supply end of roots/tubers by dividing VNFs from the consumption end by the supply-to-consumption ratio, and obtained the VNFs from the supply end in Europe and the USA as 0.85 and 1.1, respectively. The average VNF of Chinese potatoes fell between the VNFs of starchy roots in Europe and the USA. Specifically, NWC and NEC had lower VNFs, while SWC and CEC owned higher VNFs compared to the two places. The VNF of Chinese potatoes was also close to that of Austria, which was calculated as 1.19 by Liang et al. [53]. In Germany, the VNF of potatoes from the supply end reached a rather low value of 0.26 [54], showing that potato production could have a very slight N loss in some countries with advanced agricultural technologies, while China's Asian neighbor, Japan, had an apparently higher VNF of starchy roots without import trade than China, calculated as 2.71 from Shibata et al. [55].

Through Pearson's correlation analysis (Figure 3a), we knew that VNF was positively correlated with N surplus and total N input (especially chemical fertilizer N), while negatively correlated with potato yield at $p \leq 0.01$ level. As to its specific components, runoff and erosion losses were positively correlated with VNF at $p \leq 0.001$ level, and N_2O and NH_3 losses were positively correlated with VNF at $p \leq 0.01$ and $p \leq 0.05$ level. Among the different loss pathways, runoff N losses devoted the most to VNFs across the regions NEC, MEC, SEC, and SWC, occupying 35.2%, 38.1%, 62.8%, and 40.9% of their respective VNFs. NH_3 volatilization losses also made a significant contribution to VNFs and were the largest emission source to the atmosphere, ranging from 0.14 ± 0.58 in NEC to 0.41 ± 0.58 in CEC, accounting for 11.7%–30.8% of VNFs across the six regions. Significantly higher NH_3 volatilization losses were observed in CEC (0.39 ± 0.60), NC (0.30 ± 0.49), and SEC (0.24 ± 0.42) compared to the other three potato production regions. Actually, NH_3 volatilization factor is positively correlated with temperature and rainfall [56]. Because of the higher annual temperature and rainfall in south China, NH_3 volatilization loss in southern China is usually higher than that in north China [57]. Hence, how to effectively control NH_3 volatilization during or after fertilization should be emphasized in southern regions of China. Measures like using slow-release nitrogen fertilizers [58] and adding urease inhibitors like NBPT [59] can be beneficial in mitigating NH_3 losses from fertilizers. The waste of potato straw brought a certain degree of negative influence on the pedosphere. The straw pile set N loss distributed at 0.15–0.17 among different producing regions. Then, followed the leaching N losses, ranging from 0.05 ± 0.02 in NEC to 0.37 ± 0.14 in NC, accounting for 7.4%–23.8% of VNFs across different regions. NC had the highest leaching loss, followed by CEC with a value of 0.26 ± 0.13.

Under optimized practices (Figure 6b), the VNFs were reduced to some extent, ranging from 0.48 ± 0.12 in NWC to 1.22 ± 0.55 in SWC, with reduction rates varying between 11.5%–28.1%. The decrements of the VNFs were 0.12, 0.27, 0.16, 0.43, 0.19, and 0.13 in NEC, NC, NWC, CEC, SWC, and SEC, respectively. Notably, CEC had the highest VNF reduction, followed by NC, which aligned with the favorable reduction results of N input and N surplus in CEC and NC under optimized management measures. NEC and NWC exhibited low VNF reduction margins, as their VNFs had already reached relatively low levels. This meant there were low environmental impacts of potato production in the two regions originally. In contrast, SWC and SEC exhibited high VNFs under conventional practices while comparatively lower reduction amounts under optimized practices. It was primarily because the heavy rainfall in south China brought about severe N loss, which was hard to be reduced artificially by optimizing N fertilizer rates solely [60]. To effectively mitigate water stress on nutrient resources in south China like SWC and SEC, optimizing planting dates and irrigation schedules could be implemented to match crop growing demand with the supply of precipitation resources [61].

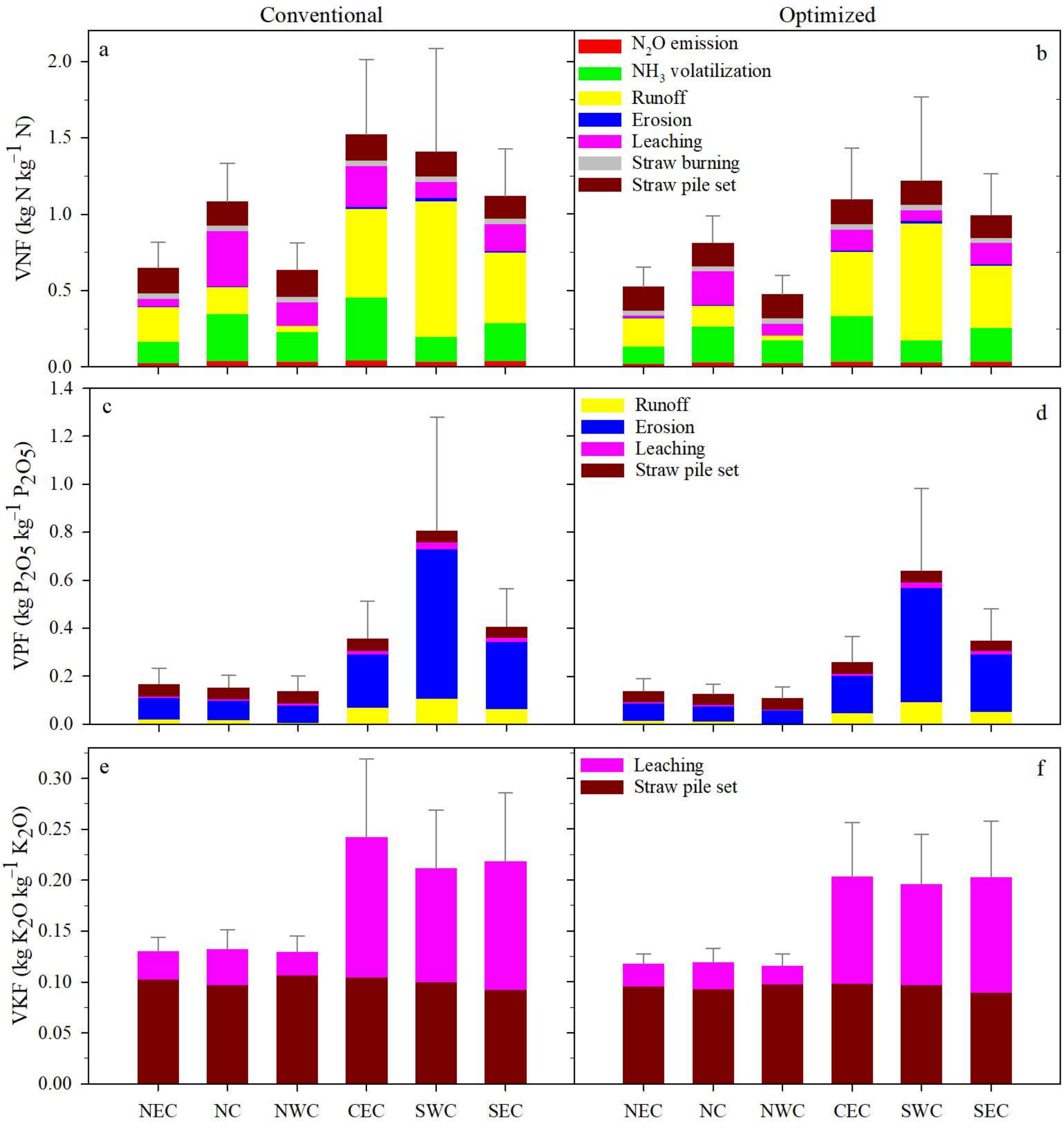

Figure 6. The VNFs (**a**,**b**), VPFs (**c**,**d**), and VKFs (**e**,**f**) of potatoes under conventional and optimized measures in the six potato production regions.

Regarding the specific reductions in the components of VNF, notable reductions were observed in N losses through runoff, NH_3 volatilization, and leaching under optimized management. The highest reduction of runoff N loss occurred in CEC at 0.15, corresponding to a reduction rate of 26.8%, and then followed by that in SWC at 0.12, with a reduction rate of 13.5%. CEC, NC, and NWC displayed substantial potential for reducing NH_3 volatilization, with reduction rates of 27.3%, 23.4%, and 23.9%, respectively. Different from the aforementioned two, the reduction amounts of leaching N loss were much higher in NC, CEC, and NWC than in the other three regions, which were 0.14, 0.13, and 0.07, with reduction rates of 39.0%, 48.5%, and 49.1%, respectively. The leaching loss was significantly correlated with the total input N, fertilizer N, as well as N surplus at $p \leq 0.01$ level (Figure 3a). In NEC, where chemical N fertilizer rates were already kept low under both conventional and optimized practices, the leaching N losses were also relatively low. NC, CEC, and NWC experienced larger reductions of N surpluses, resulting in significant decreases in leaching N losses under optimized practices. While SWC and SEC had limited potential for reducing virtual N inputs (Figure 3a,b), leading to low reductions in N surplus and leaching N loss with the current optimized practices. N_2O is a kind of trace gas emitted to the atmosphere from cropland, while it poses a severe negative impact on climate warming, with a 265 times CO_2eq warming potential over a 100-year scale, and it also contributes to ozone layer damage [62]. Reducing agricultural N_2O emissions is one of the hotspots in international soil science research. It was found that under optimized practices, CEC, NC, and NWC achieved higher N_2O emission reductions of 0.012, 0.01, and 0.008, respectively, with reduction rates of 28.5%, 25.4%, and 25.2%, outperforming the other three regions.

3.3. The VPFs of Potatoes in the Six Production Regions

Field P loss mainly happens in the pedosphere and hydrosphere, affecting surface- and ground-water by causing water eutrophication [63]. The VPFs of the six production regions were in the range of 0.14 $\pm$ 0.06–0.80 $\pm$ 0.47 kg P_2O_5 released kg^{-1} P_2O_5 in supplied potato product (omit unit in the following text) under conventional practices (Figure 6c), ranking as NWC (0.14 $\pm$ 0.06) < NC (0.15 $\pm$ 0.05) < NEC (0.17 $\pm$ 0.07) < CEC (0.36 $\pm$ 0.16) < SEC (0.41 $\pm$ 0.16) < SWC (0.81 $\pm$ 0.47). Erosion P losses accounted for the largest proportion, comprising 53.9%–77.0% of VPFs. SWC had the maximum erosion P loss at 0.62 $\pm$ 0.47, followed by SEC at 0.28 $\pm$ 0.15 and CEC at 0.22 $\pm$ 0.15. The terrain of SWC primarily consists of plateaus and mountains, and the farmland is mostly sloping land with a relatively large slope and altitude difference [64]. Thus, soil erosion loss is rather serious in SWC. The second major contributor to VPF was the straw pile set, with the P loss values distributed around 0.046–0.053. P losses through runoff and leaching were relatively low, varying around 0.004 $\pm$ 0.003–0.10 $\pm$ 0.08 and 0.006 $\pm$ 0.003–0.03 $\pm$ 0.02, respectively. P is a relatively slow-moving element in the soil and has a high trend to remain in the soil for extended periods as residual P [65]. As depicted in Figure 4, the soil P accumulation amounts were rather high, distributed at 48.2–128.4 kg P_2O_5 ha^{-1} under conventional measures and 37.5–100.0 kg P_2O_5 ha^{-1} under optimized measures in the potato production regions. As reported by Li and Jin [66], an average of 240 kg ha^{-1} P accumulated in the soil from 1980 to 2007, brought about soil Olsen-P increasing from 7.4 to 24.7 mg kg^{-1}. P accumulation in soil can enhance the P supply capacity of the soil, contributing to increased crop yield, while excessive soil P accumulation is liable to bring potential environmental risk. Human-induced increases in GHG emissions have given rise to more frequent heavy precipitation events across about two-thirds of data-covered regions in the Northern Hemisphere land [67]. Heavy precipitation combined with high soil P is easy to further aggravate P losses through erosion and runoff. Due to soil accumulation, VPF as well as its constituents did not have a significant correlation with chemical or manure P input and P surplus, as shown in Figure 3b.

The VPFs were reasonably reduced to 0.11 $\pm$ 0.06–0.63 $\pm$ 0.34, with reduction rates ranging from 14.1% to 27.0% across the six regions under optimization measures (Figure 6d). An obvious reduction was observed in erosion P loss, with the decrements reaching 0.02–0.15, accounting for 66.0%–88.0% of the respective reduction amounts of VPFs in the six regions. Other P loss pathways, such as runoff, leaching, and straw pile set, showed relatively low reduction intervals. Although SWC had the highest decrement in erosion P loss, it still remained significantly higher than the other regions. Hence, additional technical measures beyond decreasing P fertilizer rates are needed to further reduce P inputs and losses in SWC. Applying soil P activators, e.g., humic acid, lignin, phosphatase, etc., is an effective approach to activate insoluble P accumulated in soil and promote the transformation of soil P forms, thereby increasing the use efficiency of soil accumulated P and decreasing P inputs [68]. Additionally, utilizing soil phosphate solubilizing microorganisms (SPSMs) can help reduce P loss through P fixation and enhance plant roots' absorption of P by accelerating their P turnover [69]. It is recommended to utilize soil P activators and SPSMs in potato fields, especially in SWC, to take advantage of soil residual P and reduce the risk of P erosion loss.

3.4. The VKFs of Potatoes in the Six Production Regions

The VKFs of potatoes had a small range compared to VNF and VPF, which were in the range of 0.13 ± 0.02–0.24 ± 0.08 K_2O released kg^{-1} K_2O in supplied potato product (omit unit in the following text) under conventional practices (Figure 6e), with a rank of NWC (0.13 ± 0.02) ≈ NEC (0.13 ± 0.01) ≈ North China (0.13 ± 0.02) < SWC (0.21 ± 0.06) < SEC (0.22 ± 0.07) < CEC (0.24 ± 0.08). The VKFs were notably lower than the VNFs in the six potato production regions. K losses through the straw pile set were similar among different regions, concentrated between 0.09–0.10. As southern China had high K leaching rate than northern China [29,30], the K leaching losses of three southern regions CEC, SWC, and SEC were 0.14, 0.11, and 0.13, and of three northern regions NEC, NC, and NWC were 0.03, 0.04, and 0.02, respectively. If all potato straws were recycled without any waste, VKFs could be largely decreased to 0.02–0.13.

Under optimized practices, the VKFs were reduced to 0.12 ± 0.01–0.20 ± 0.05, with limited room for reductions (Figure 6f). As analyzed before, total K inputs should be increased to at least meet the crop's K uptake requirements, which were among 253.7–312.2 kg K_2O ha^{-1} of the six production regions under optimized management. These suggested K input amounts were close to the recommended fertilizer value of 300 kg K_2O ha^{-1} in northern China, as reported by Wang et al. [70]. VKF and K leaching loss showed positive correlations with K input and K surplus at $p \leq 0.01$ level, and negative correlation with potato yield at $p \leq 0.05$ level (Figure 3c). Thus, to control VKF, it is important to increase K input to an appropriate level and simultaneously improve potato yield with effective measures. Combined application of organic and inorganic fertilizers is a recommended method to maintain soil K balance and reduce the depletion of soil K by crops [71]. Straw returning to the field is also a good measure to supplement K and improve soil fertility, given that crop straws are typically rich in K elements [72]. With the improvement of K inputs and potato yield, the use efficiencies of K, as well as N and P, would increase, which will restrict VKF and be conducive to reducing VNF and VPF correspondingly.

3.5. Virtual N, P, and K Losses in the Six Potato Production Regions

In 2020, the potato yields of NEC, NC, NWC, CEC, SWC, and SEC were 4.1×10^5, 7.9×10^5, 26.0×10^5, 6.6×10^5, 42.5×10^5, and 2.9×10^5 Mg, accounting for 4.6%, 8.7%, 28.9%, 7.3%, 47.2%, and 3.3% of the national total potato yield, respectively [24]. Based on the above analyses about VNF, VPF, and VKF, we calculated the total virtual N, P, and K losses to the environment in the six potato production regions, as shown in Figure 7. SWC had the highest VN, VP, and VK losses, amounting to 2069.3×10^5, 1138.8×10^5, and 324.9×10^5 Mg, respectively, representing 72.5%, 86.5%, and 68.3% of the whole under conventional measures. As there are large potato-sown areas in SWC, where a mixture cultivating pattern of one or two cycles a year is commonly used, it is essential to urgently implement effective measures to reduce nutrient losses in potato production. The optimized practices had reduced 13.8%, 20.6%, and 7.5% of VN, VP, and VK losses in SWC by mainly reducing inputs of chemical fertilizers. As the VN, VP, and VK losses still dominated those of the whole of China under optimizing measures, it is vital to reduce VNF, VPF, and VKF of potato production in SWC with further optimized measures. Regulating planting dates and irrigation schedules, managing water and fertilizers integrated, and applying soil P activators or SPSMs to utilize soil accumulated P are proposed methods to reduce nutrient losses.

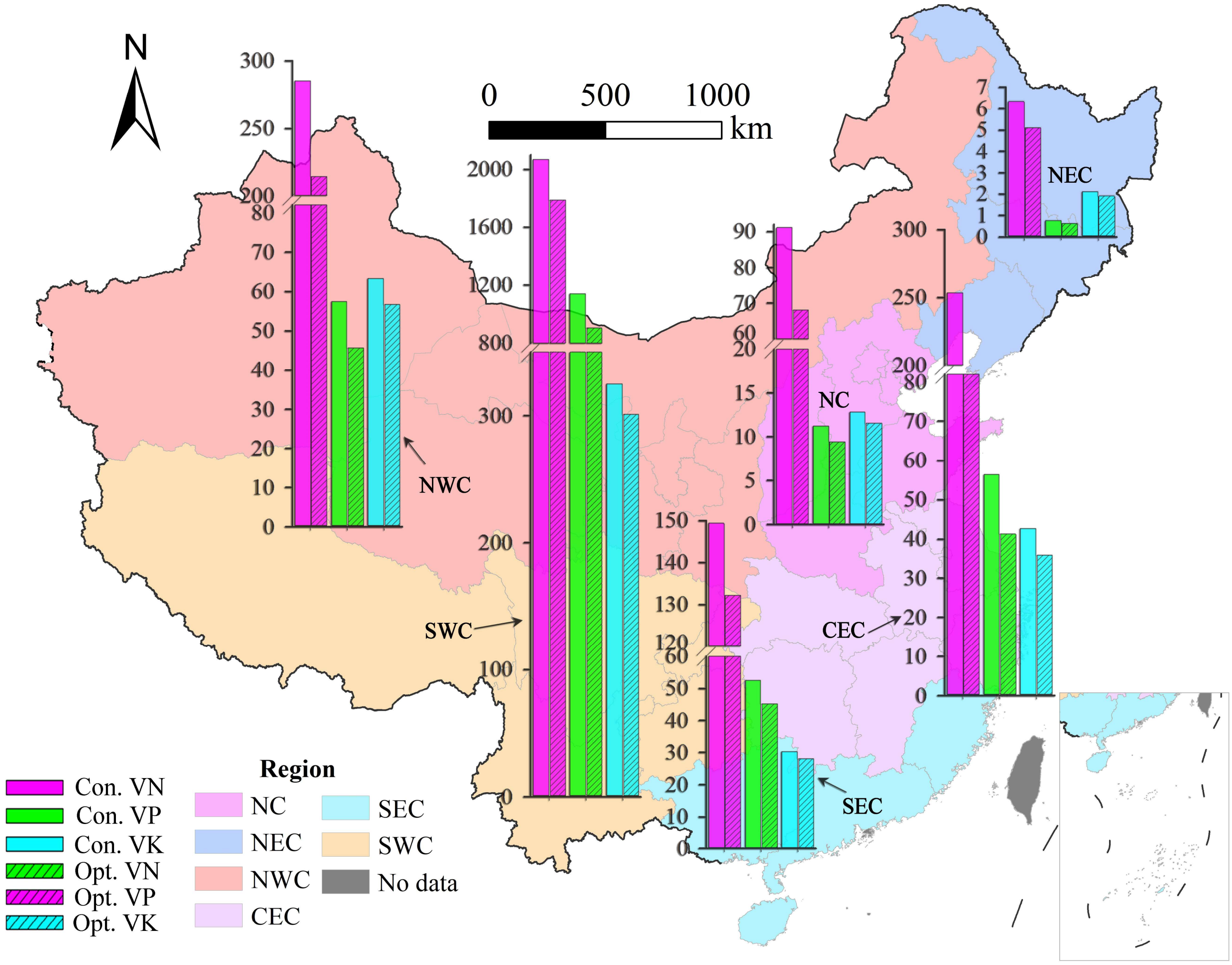

Figure 7. Virtual N, P, and K losses of the six potato production regions under conventional and optimized measures and the reduction amounts (unit: VN loss: 10^3 Mg N, VP loss: 10^3 Mg P_2O_5, VK loss: 10^3 Mg K_2O). Note: Con. means under conventional practices, Opt. means under optimized practices.

NWC was the second highest losses region. Its VN, VP, and VK losses accounted for 10.0%, 4.4%, and 13.3% of the national whole under conventional practices, and accounted for 9.0%, 4.4%, and 13.0% of the whole under optimized practices, respectively, with reduction rates reached 24.9%, 20.4%, and 10.5%, respectively. As the total N, P inputs were lower (Figures 2 and 4), potato yield was higher [1] than in other regions except for NEC, and the VNF, VPF, and VKF were the lowest (Figure 6) under both conventional practices and optimized practices, NWC is a suitable region for potato production. Then followed the CEC, with VN, VP, and VK losses accounting for 8.9%, 4.3%, and 9.0% of the national whole under conventional practices, and being reduced by 27.1%, 26.8%, and 16.0% with optimized measures. SEC ranked next, with VN, VP, and VK loss rates accounting for 5.2%, 4.0%, and 6.3% of the national whole under conventional practices and being reduced by 11.5%, 14.0%, and 7.1%, respectively, while the reduction rates were lower than the other regions. In addition to reducing fertilizer inputs, additional efforts are needed to address the impact of high temperatures and heavy rainfall on nutrient losses in SEC. Strategies such as applying slow-release nitrogen fertilizers or urease inhibitors to minimize NH_3 volatilization loss and scheduling winter potatoes after late-rice harvest to avoid rainy and hot weather seasons could be beneficial. NC had relatively low VN, VP, and VK loss rates, accounting for 3.2%, 0.9%, and 2.7% of the national whole under conventional practices and being decreased by 25.3%, 16.1%, and 9.9%, respectively, under optimized practices.

Both CEC and NC showed great potential for reducing fertilizer inputs (especially N and P fertilizer inputs), VNF, and VPF.

The lowest VN, VP, and VK losses emerged in NEC, accounting for only 0.2%, 0.1%, and 0.4% of the national whole under conventional practices. It was mainly determined by the relatively low VNF, VPF, and VKF, as well as the small potato sown area in NEC. The optimized measures resulted in a 19.1%, 16.2%, and 9.6% reduction of VN, VP, and VK losses, respectively. As potato production in NEC only needs low nutrient inputs while bringing about low environment costs with high yield under optimized measures, NEC is suitable for growing potatoes, and the sown area could be expanded appropriately, for example, converting some corn fields to potato fields [73], or performing corn–potato or soybean–potato crop rotation systems [74].

Overall, the key regions to reduce VN, VP, and VK losses of potato production are SWC, NWC, and CEC. To effectively mitigate environmental impacts, targeted optimization measures should be adopted based on the specific conditions of nutrient inputs and emission factors, as discussed earlier. The Chinese government has proposed adjusting plant structures and promoting potato production in different regions, particularly in the "Sickle Bay Area"—NEC, NWC, and SWC [74]. Encouraging potato cultivation in NEC and NWC is desirable since potato growing there brings about relatively low environmental influence when managed optimally. Restricted by limited arable land areas, it is more important to take measures to raise the per unit potato yield, so as to increase the use efficiencies of N, P, and K, boost economic benefit, and decrease VNF, VPF, and VKF of potato production. Alongside the above suggested regional optimization measures, other agronomic measures such as promoting the use of virus-free, drought- and disease-resistant potato seeds, adopting advanced planting mechanization technologies, implementing straw mulching, and practicing conservation tillage [61,75,76] are highly recommended to increase per unit potato yield and mitigate environmental effects.

4. Conclusions

Regional natural resource and planting management conditions in China result in various spatial characteristics of potato production inputs/outputs and environmental effects. With the input–output analysis method, we first conducted a comprehensive calculation of the VNFs, VPFs, and VKFs of potatoes in six potato production regions in China, encompassing the entire potato production period prior to consumption. Among the production regions, NEC and NWC stood out as the most suitable producing regions as they had high yields with low inputs, VNFs and VPFs. It is suggested to expand the sown area in the two regions by adjusting the planting structures. By optimizing N input practices, NC and CEC had great VNF reduction effects, while SWC and SEC faced high VNFs but low reduction rates. SWC is the most crucial region for reducing N and P losses as it has the largest planted area and the highest VNF and VPF under current optimized practices. Site-specific optimization measures considering local environmental conditions, e.g., optimizing planting time and adopting fertigation are necessary to further reduce the environmental effects in SWC. There is considerable potential for reducing fertilizer P input in NC, CEC, SWC, and SEC by improving the utilization of the substantial amount of soil residual P. Moreover, K inputs in most regions, except SEC, were found to be insufficient, calling for an increase to maintain soil fertility soil and eliminate the negative effects of K deficiency on yield. The comprehensive input–output analyses of regional N, P, and K provide reliable regional parameters on VNF, VPF, and VKF for potato production, which are vital for evaluating regional environmental costs and are of great significance in achieving efficient and sustainable development of potato production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13092430/s1, Table S1: Agronomy inputs, yields, and commodity ratios of potato production system under farmers' conventional and optimized measures in different agricultural regions; Table S2: Manure application amount, N, P and K amount of potato system in different agricultural regions; Table S3: Seed weight, amount and plant density of potato in different agricultural regions; Table S4: Contents of N, P and K in different forms of manures; Table S5: Contents of N, P and K in potato seed; Table S6. Contents of N, P and K in irrigation water; Table S7: N and P deposition amounts in different regions; Table S8: K deposition in different regions (Mean±SD); Table S9: Crop nutrient uptake (kg) for producing 1 Mg (1 Mg = 10^6 g) fresh potato in China; Table S10: N_2O emission factors of chemical fertilizers and manures from upland in China; Table S11: NH_3 volatilization factors of chemical fertilizer and manure from upland in six potato production regions of China; Table S12: N and P emission factors via runoff, erosion, leaching and denitrification in six potato production regions of China.

Author Contributions: Conceptualization, B.G. and S.C.; methodology, X.F.; software, D.Z.; validation, B.G., D.Z. and X.F.; formal analysis, X.F. and W.H.; investigation, D.Z.; resources, D.Z.; data curation, W.H.; writing—original draft preparation, X.F. and B.G.; writing—review and editing, B.G. and W.H.; visualization, M.J.A. and W.Z.; supervision, S.C.; project administration, B.G.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

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