Research Progress and Prospects of Potassium Balance in Chinese Farmland Soils (Postprint)

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Abstract

The soil potassium balance method is a simple and practical approach for assessing the sufficiency/deficiency status of soil potassium pools, widely applied in evaluating potassium nutrient supply status in cropland soils and scientific fertilization practices. This paper, from the perspective of cropland nutrient balance, reviews the major advances in research on cropland potassium balance in China in recent years through analyzing four aspects: the calculation methods of potassium balance, spatiotemporal variation characteristics of cropland potassium balance, potassium balance status in croplands with different crops, and the effects of potassium balance on soil potassium content. Research indicates that China's cropland potassium balance overall shows a deficit, and in the temporal dimension displays a trend of first decreasing then increasing since the founding of the People's Republic of China; however, performance varies among different regions with large variation, and the potassium balance status in some regions shows a surplus; potassium balance among different regions and crops exhibits a "polarization" development trend; differences in nutrient uptake characteristics among crops and fluctuations in fertilizer and agricultural product market prices are two factors that jointly determine the differences in potassium balance between different crop types and inter-annual variations for the same crop; different researchers have obtained considerably different results regarding China's cropland potassium balance in terms of total surplus amount, surplus amount per unit area, and spatial variation characteristics, and it is advisable to conduct comparisons after comprehensive analysis of the selected indicator systems rather than making direct comparisons; whereas research results regarding temporal variation, potassium balance in croplands with different crop planting types, and soil potassium accumulation patterns are basically consistent; essentially, the current status of soil nutrient pools is the result of accumulation over many years of a region's cropping system and fertilization practices, while also determining its future development trend. To maintain the stability and improvement of soil potassium nutrient pools, based on the current status of potassium balance research in China, this paper proposes several research directions for improving cropland potassium balance technical measures in the future, including nutrient equilibrium, increasing sources and reducing losses, emphasizing annual management of potassium under different crop rotation scenarios, and focusing on deeper stratified soil potassium nutrient pools.

Full Text

Farmland Potassium Balance in China: A Review

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Abstract: Soil potassium balance is an indicator for potassium input and output in croplands and a simple method to judge the situation of soil potassium deficiency, which has been extensively used in soil nutrient condition evaluation and fertilizer recommendations for crops. This paper reviews recent research progress on farmland potassium balance in China from four perspectives: calculation methods, spatio-temporal variability characteristics, potassium balance under different cropping systems, and the influence of potassium balance on soil potassium content. Studies show an overall deficient potassium balance in Chinese croplands, which temporally exhibited a decreasing trend followed by an increase since the founding of the People' s Republic of China. However, regional variations were significant, with surplus potassium observed in some areas, resulting in a "polarization" of potassium balance. Differences in nutrient uptake characteristics among crops, together with fertilizer volatility and agricultural market prices, jointly determine variations in potassium balance between crop types and across years for the same crop. Different researchers have reported substantial discrepancies in total surplus/deficit amounts, per-unit-area balances, and spatial variation patterns of potassium balance in China. Therefore, direct comparison of these results is inappropriate; instead, comprehensive analysis of selected indicator systems is recommended before making comparisons. In contrast, research findings on temporal variation, potassium balance under different cropping systems, and soil potassium accumulation patterns are generally consistent. Essentially, the current soil nutrient pool status results from long-term accumulation of regional cropping systems and fertilization practices, which in turn determines its future development trajectory. To maintain and improve soil potassium pools, future research should focus on nutrient balance optimization, resource conservation and alternative sources, annual potassium management under different rotation systems, and deeper soil layer potassium pools.

Keywords: Cropland; Potassium balance; Potassium deficiency; Potassium polarization; Soil potassium pool

Potassium is one of the three essential macronutrients for plants. China has become the world' s largest consumer of potassium fertilizer, yet potassium resources are relatively scarce, with domestic production meeting only half of the demand. Soil potassium pools and supply intensity largely determine the efficiency of potassium fertilizer input. Scientific application of potassium fertilizer tailored to location, timing, and crop type is crucial for improving crop yield and quality while rationally utilizing this valuable resource. The apparent nutrient balance method, which calculates the difference between nutrient input and output in farmland soils, provides a simple and practical approach for assessing soil nutrient pool status. It has been widely applied to evaluate soil nutrient supply conditions and guide scientific fertilization for grain crops, vegetables, and fruit trees [1-6]. Meanwhile, the basic status of farmland nutrient balance at the national or regional level determines the development trend of farmland nutrient levels [7]. As potassium fertilizer has demonstrated increasing effectiveness from south to north since the 1970s, what is the current status of potassium balance in China? What are the national, regional, and crop-specific situations, and how does potassium balance affect soil potassium pools? This paper reviews recent research on potassium balance across different scales in China from the perspective of farmland management, examining both calculation methods and surplus/deficit conditions, and discusses technical approaches for improving farmland potassium balance and enhancing cultivated land quality.

1 Calculation of Farmland Potassium Balance

Farmland potassium balance is calculated by taking the farmland as the research object, measuring all potassium inputs and outputs, and then subtracting them. A positive value represents potassium surplus, while a negative value represents potassium deficit: Potassium Balance = Potassium Input - Potassium Output. Potassium inputs mainly include chemical and organic fertilizers, as well as atmospheric wet and dry deposition, irrigation water, and crop seeds. Li Shutian et al. [8] summarized nationwide data, proposing that potassium input through wet and dry deposition averages 8.3 kg · hm ^{2} per year, nutrients brought into farmland through irrigation water average 14.8 kg · hm ^{2} per year, and data for seed input varies by crop but is relatively easy to obtain.

Potassium outputs include potassium absorbed by crops (both grain and straw) and potassium losses. Crop uptake can be estimated based on economic yield and the amount of potassium required per unit of economic yield. Potassium absorption varies by crop, with reference values readily available, though more precise local values can be obtained through field experiments. Potassium loss is primarily through leaching in paddy fields, averaging about 12 kg · hm ^{2} in southern China [9] and 6 kg · hm ^{2} in northern China [10]. Upland soils generally experience no leaching loss, and potassium ions are easily adsorbed or fixed by soil, reducing losses; moreover, fixed potassium remains effective for subsequent crops, so potassium loss in upland soils can be considered negligible [8].

2 Potassium Balance Status in Chinese Croplands

Researchers have studied soil potassium balance in China at various scales and from different perspectives. Studies range from national and provincial scales to watershed and county scales. Common approaches include calculating potassium surplus/deficit ratios and per-unit-area balance intensity to compare regional differences, while some studies conduct specialized surveys on crop-specific potassium balance to compare differences between crops or the same crop across regions. The following sections review potassium balance amounts (surplus/deficit), regional differences, temporal variation characteristics, crop-specific farmland potassium balance, and the impact of potassium balance on soil potassium pools (trends in soil potassium changes).

2.1.1 Spatial Variation Characteristics of Farmland Potassium Balance in China

2.1.1.1 Potassium Balance Amount (Surplus/Deficit) Most studies, whether based on monitoring data or statistical analysis, conclude that China' s overall potassium balance is deficient [7,11-13], although some researchers suggest that national potassium input and output are basically balanced [8]. Regarding absolute surplus/deficit amounts, calculation results vary significantly among researchers due to differences in study years, methods, and parameters, requiring careful analysis rather than direct citation. Table 1 summarizes recent calculations of national and regional farmland potassium balance in China. The table shows substantial differences even for the same research object (e.g., post-2000 national data), with total potassium balance ranging from -3.9×10 t [14] to 4.3×10 t [8], and per-unit-area balance ranging from -74 kg · hm ^{2} [12] to 15.53 kg · hm ^{2} [15].

2.1.1.2 Regional Balance Comparing potassium balance status across different regions is a fundamental research component. Table 1 also reveals discrepancies among researchers regarding the degree of potassium deficit or surplus across regions. National cultivated land monitoring results indicate that all six major regions experienced varying degrees of potassium deficit in 2006, with the Northwest region showing the most severe deficiency [12]. Li Shutian et al. [8] identified deficit regions in Northeast, North, and middle-lower Yangtze areas, while Fang Yudong et al. [14] pointed to central-western regions, eastern areas, southern Xinjiang, and some counties in Heilongjiang. Li Shutian et al. [8] considered the Northwest region to have balanced input-output, with surplus only in Southeast and Southwest regions. Lu Rukun et al. [7] found that among six southern provinces, three (Fujian, Guangdong, Guangxi) had surpluses while the other three (Zhejiang, Jiangxi, Hunan) had deficits. Cheng Linlin [16] noted that counties with high potassium balance were concentrated in western regions like Tibet, Xinjiang, and Inner Mongolia, while intensively cultivated southeastern regions such as Henan, Hubei, Jiangsu, and Anhui mostly showed negative potassium balance.

These discrepancies arise not only from differences in study periods, methods, and parameters as mentioned above, but also from different regional divisions. Even for national-scale zoning, some studies used six regions while others used seven. Among those using six regions, specific divisions differed: Li Shutian et al. [8] divided into Northeast, North, middle-lower Yangtze, Northwest, Southwest, and Southeast; the National Agro-Tech Extension Center used North, Northeast, East, South, Northwest, and Southwest [12]; while Cheng Linlin [16] used seven regions: North, Northeast, East, Central-South, Northwest, Southwest, and South China. These different zoning schemes inevitably lead to different results.

2.1.2 Temporal Variation Characteristics of Soil Potassium Balance in China

Despite varying results for potassium balance amounts, researchers generally agree on the trend of soil potassium balance status: since the founding of the People' s Republic of China, the national trend has been decreasing followed by increasing, though regional patterns differ. This reflects the comprehensive effects of potassium input and output across different historical periods. As mentioned previously, direct comparison is inappropriate due to differences in parameters, systems, and study periods. Table 2 presents selected research results on these temporal trends.

Cheng Linlin's [16] calculations show that from 1951 to 2004, China's potassium balance remained in deficit, with an overall trend of decrease followed by increase. Regional patterns varied: from 1995 to 2004, the five North China provinces and three South China provinces showed continuously increasing potassium balance; East China maintained a relatively stable state; while Northwest and Southwest regions decreased in the first three years then slightly increased. Lu Rukun et al. [7] summarized potassium balance over 40 years since 1949, finding the deficit rate remained around 40%. Their later study on six southern provinces from 1986-1995 found that while three provinces had surpluses, the deficit in the other three provinces eased over the decade, leading to recommendations for potassium conservation in surplus regions [20]. National soil monitoring results over more than 20 years (1985-2006) showed a decreasing trend in potassium deficit in the first decade, followed by a slight increase in the latter decade. Regional historical analysis revealed increasing potassium deficit in North China, stable status in Northeast China, and decreasing deficits in East, South, Northwest, and Southwest China [12].

2.2 Farmland Potassium Balance Under Different Cropping Systems in China

Potassium balance among different crops is influenced by two factors: varying nutrient absorption characteristics among crops (e.g., vegetables, fruit trees, and tobacco have high potassium demand) and potassium fertilizer input affected by fertilizer and agricultural product market prices. These factors jointly determine differences in potassium balance between crop types and across years for the same crop. Some studies also suggest potassium balance correlates with economic, social, and educational indicators [21].

Under several typical rotation systems in China, soil potassium balance status is as follows: wheat (*Triticum aestivum*)-maize (*Zea mays*) rotation shows an apparent deficit of 107.8 kg · hm ^{2} with a balance ratio of -44.7%; early rice (*Oryza sativa*)-late rice rotation shows a deficit of 66.6 kg · hm ^{2} with a balance ratio of -46.3%; and rapeseed (*Brassica campestris*)-rice/maize/cotton (*Gossypium sp.*) rotation shows a deficit of 52.5 kg · hm ^{2} with a deficit rate of -33.7% [12]. The potassium deficit in grey desert soil under wheat-maize-cotton rotation is gradually increasing [22]. Six cropping systems in Hubei Province (rapeseed-cotton, fallow-cotton, rapeseed-rice, wheat-rice, early rice-late rice, and single-season rice) show an average annual deficit of 52.4 kg · hm ^{2} [23]. In a rice-barley (*Hordeum vulgare*) rotation system, soil potassium still showed deficit even with annual potassium application of 187.5 kg · hm ^{2} (K O) [24].

Studies on winter wheat-summer maize in different regions indicate that without potassium fertilizer or straw return, the annual apparent potassium deficit ranges from 134-258 kg · hm ^{2} in North China and 220-261 kg · hm ^{2} in Northwest China [13]. Our 2015 survey of five rotation types in the North China Plain found three rotation types in deficit (winter wheat-summer maize, winter wheat-peanut (*Arachis hypogaea*), winter wheat-soybean (*Glycine max*)) and two in surplus (wheat-cotton, garlic (*Allium sativum*)-cotton), with deficits in winter wheat-summer maize and winter wheat-peanut rotations exceeding 200 kg · hm ^{2} (unpublished data, 2016). Typically, potassium application rates for economic crops are 1.4-2.6 times those for grain crops. Analysis of over 50,000 soil samples also showed that soil available potassium content in economic crops increased faster than in grain crops from 1990-2012 [25]. Protected vegetables in Shandong showed a potassium surplus of 3,437 kg · hm ^{2} [26].

Due to the special nutrient requirements of flue-cured tobacco (*Nicotiana sp.*), potassium fertilizer used in tobacco production accounts for a significantly higher proportion of national potassium fertilizer consumption than nitrogen or phosphorus fertilizers. In contrast to the apparent potassium deficit in China, tobacco-growing regions show clear potassium surplus. While excess potassium does not threaten the environment like nitrogen and phosphorus, it causes resource waste and directly affects economic benefits and farmers' income. Research shows the national average output/input ratio for tobacco potassium is 27.7%, with significant regional differences—northern tobacco regions have higher output/input ratios than southern regions [27-28].

2.3.1 Effects of Potassium Fertilizer Application on Soil Potassium Pools

Regional farmland nutrient surplus/deficit is a major driver of spatio-temporal changes in soil fertility. Research on farmland soil fertility evolution at six agricultural ecological experimental stations (Hailun, Shenyang, Luancheng, Changwu, Changshu, Yingtan) showed that farmland potassium surplus/deficit was significantly correlated with annual changes in soil available potassium, with potassium balance determining the direction of soil potassium nutrient changes [17]. Other studies found that potassium surplus under different crops and rotation patterns was positively correlated with surface soil (0-30 cm) available potassium content at harvest, though not significantly [29]. Long-term negative potassium balance leads to depletion of soil exchangeable potassium [30]. Various potassium-containing materials (rice straw, straw ash, silicon-calcium-potassium fertilizer, citrate-soluble potassium fertilizer, and potassium chloride) can significantly increase different forms of soil potassium [31].

Xu Minggang et al. [32] summarized the evolution of available potassium in typical farmland soils under long-term fertilization: without potassium fertilizer, soil available potassium content decreases, especially in southern regions; with appropriate potassium application, soil available potassium can maintain its original level; and combined chemical and organic fertilizer application significantly increases soil available potassium.

A 16-year field experiment on calcareous cinnamon soil under single-cropping conditions in Shanxi showed that with only nitrogen and phosphorus application, soil potassium had an average annual deficit of 104.3 kg · hm ^{2}, with soil available and slowly available potassium decreasing by 23.6% and 14.3%, respectively, compared to initial values. However, annual potassium application plus wheat straw return increased soil available and slowly available potassium by 38.6% and 11.0%, respectively [33]. In a manural loess soil wheat-maize rotation system, long-term potassium application significantly increased soil available potassium, though available potassium in long-term no-potassium treatments did not significantly decrease. Regardless of potassium application, soil non-exchangeable potassium and HNO -extractable potassium were significantly lower than pre-experiment levels [34]. A 14-year field experiment in a red paddy soil system showed that without fertilization or with only chemical fertilizer, soil potassium was severely deficient, with the NP treatment (without K) showing the most severe deficit at 120.1 kg · hm ^{2} annually. Organic nutrient cycling fertilization systems could substantially reduce paddy soil potassium deficit or even create surplus [35].

2.3.2 Trends in Soil Potassium Pools

Long-term experiments and national soil surveys indicate that since the founding of the People' s Republic of China, except for some areas where soil available potassium increased, the overall national trend has been depletion year by year, with the area of potassium deficiency continuously expanding [36].

2.3.2.1 Trends in Soil Available Potassium Content Soil available potassium is the potassium that can be utilized by crops in the short term, making its study crucial for rational potassium fertilizer utilization and improved application effectiveness. National cultivated land monitoring results from 1985-2006 (20 years) show that national topsoil available potassium increased steadily from 76 mg · kg ^{1} in 1985 to 127 mg · kg ^{1} in 2006, with an average annual increase of 2 mg · kg ^{1} [37]. Regional and temporal analysis shows that from 1987-1997, North, East, and South China showed significant increasing trends, while Northeast, Northwest, and Southwest China showed decreasing trends. From 1998-2006, Northeast, North, East, and South China showed increasing trends, while Northwest and Southwest China remained relatively stable.

Soil available potassium distribution in China generally shows a pattern of lower levels in the south and higher levels in the north. He et al. [25] analyzed 58,559 soil samples, finding available potassium increased from 79.8 mg · L ^{1} in the 1990s to 93.4 mg · L ^{1} in the 2000s. Over the past 20 years, Northeast China showed no significant change, while North, Southeast, and Southwest China increased by 34.8%, 17.9%, and 30.2%, respectively, and Northwest China decreased by 75.9%.

Numerous regional soil potassium pool studies exist. For example, black soil regions showed varying degrees of available potassium reduction, averaging 40 mg · kg ^{1} (about 20% of the total). Fluvo-aquic soil regions showed large spatial variation—some areas increased (Beijing Tongzhou, Shandong Ling County) while others decreased (Hebei Quzhou), related to fertilization management [38]. The North China Plain has abundant data and numerous studies. Research in Hebei' s winter wheat-summer maize rotation area showed significant increases in soil available potassium compared to the second national soil survey [39-40], with further studies showing increases in Hengshui and Langfang but stable levels in other areas (Baoding, Cangzhou, Handan, Shijiazhuang, Xingtai) [41]. In Quzhou County, Hebei, soil available potassium showed a decreasing trend over 30 years (1980-2010), with rapid decline in the first 20 years and slight overall decrease with local increases in the last 10 years [42]. In Huaian County, Jiangsu, soil available potassium showed an increase-decrease-stable-slight decrease pattern from 1982-2013 [43]. In Yulin, Shaanxi, soil available potassium improved over nearly 30 years [44].

2.3.2.2 Trends in Soil Slowly Available Potassium Content Slowly available potassium serves as an indicator of soil potassium supply potential, as its continuous release can maintain available potassium at appropriate levels. When evaluating long-term soil potassium supply potential, slowly available potassium content should be the primary consideration. National cultivated land monitoring results show average topsoil slowly available potassium content of 661 mg · kg ^{1}. Regionally, Northwest China has the highest content, followed by Northeast and North China, all above the national average, while South, East, and Southwest China have the lowest content, generally below the national average [12].

3 Countermeasures and Considerations for Improving Farmland Potassium Balance in China

Potassium is an essential macronutrient for plants and a valuable non-renewable resource requiring rational utilization. Soil potassium content is fundamental to studying soil nutrient supply capacity, while nutrient levels depend on the cumulative effects of multi-year nutrient balance in farmland, particularly for potassium which has no volatilization loss and low seasonal utilization efficiency. Theoretically, continuous surplus of an element increases its soil content, while continuous deficit decreases it. However, due to the large capacity of soil potassium pools and the replenishment system from slowly available to available potassium, the short-term response of soil available potassium to farmland potassium balance may not be immediately apparent. Nevertheless, farmland potassium balance calculation remains a convenient and important indicator for monitoring soil potassium pool dynamics, predicting future development trends, and assessing soil supply capacity and fertility direction.

The balance equation shows that improving farmland potassium balance fundamentally requires coordinating inputs (potassium sources) and outputs (removal through yield, nutrient loss, etc.). With understanding of annual rotation crop potassium absorption characteristics and soil potassium pool supply features, regions can rationally apply potassium fertilizer according to location, timing, and crop.

3.1 Nitrogen-Potassium Balance and Nutrient Optimization

Research shows that the yield-increasing benefits of the three macronutrients (N, P, K) have changed significantly compared to the 1980s. Nitrogen' s yield effect has decreased markedly, while phosphorus and potassium effects have increased, with potassium showing the highest economic input-output ratio among major crops in China [15]. The proportion of potassium should be increased in both nutrient input ratios and crop absorption-to-input ratios.

Since compound fertilizers dominate current farmland fertilization, regional formulations can be adjusted based on local potassium balance status to modify potassium proportions, supplemented by crop-specific formulas to coordinate potassium nutrition balance among different crops.

3.2 Multiple Measures: Developing Sources and Reducing Losses

Due to severe shortages of chemical potassium fertilizer resources in China, potassium supply must still rely on organic sources. China has enormous organic fertilizer resources, with total potassium input to national farmland estimated at 22.97 million tons, of which chemical fertilizer accounts for only 37.6%, organic fertilizer accounts for 53.8% (including 34.9% from human and animal manure and 17.5% from crop straw return) [8]. Unlike chemical potassium fertilizer with high potassium content, organic fertilizer has lower potassium content with significant variations in content and release characteristics among different types. Before application, careful understanding of local organic potassium source characteristics is recommended. Studies on potassium cycling rates of different organic fertilizer types under various regional climate conditions should be conducted to provide technical support for rational organic fertilizer application and soil potassium pool improvement.

Numerous domestic and international experiments have confirmed that the optimal treatment for maintaining soil potassium balance, reducing crop consumption of soil potassium, and mitigating soil potassium fertility decline is combined organic-inorganic application [34,45-48]. Given the continuously decreasing proportion of organic fertilizer application in China, strengthening promotion in this area is essential.

Straw return is a fundamental measure for improving soil fertility and an excellent potassium supplementation method [49-51]. Most experimental studies show that straw return significantly increases soil available potassium. As China is extremely deficient in potassium fertilizer resources, and unlike nitrogen and phosphorus which concentrate in grain, crop straw and stubble contain 70%-80% of plant potassium. Straw return through various methods is therefore critically important for supplementing potassium resources and deserves high attention [52].

While developing sources, reducing losses is equally important. Balanced fertilization and increased vegetation coverage can minimize soil potassium loss. Research shows that excessive potassium application significantly increases leaching of exchangeable potassium [53], particularly in sandy soils [54]. Potassium loss increases with rainfall intensity, while balanced fertilization improves plant coverage, reduces soil erosion and nutrient runoff loss, and enhances nutrient utilization efficiency [55].

3.3 Strengthening Research on Crop Rotation Effects and Annual Potassium Management

Changes in soil nutrient pools result from long-term accumulation of regional cropping systems and fertilization practices. Different crops have varying nutrient absorption characteristics that can be used to adjust soil potassium pools. For example, in areas with long-term potassium deficit, besides potassium fertilizer application, planting crops with relatively low potassium absorption or configuring appropriate crop rotations can help restore soil potassium pools.

Crop rotation is a long-term human adaptation to local climate, soil, cultivation conditions, and practices that remains relatively stable over time. Different rotations directly determine nutrient input and output, thus affecting nutrient balance status. The rotation cycle is the basic unit determining soil nutrient pool development. Nutrient balance calculations typically focus on a single crop season, but future research should pay more attention to annual nutrient balance of multi-crop combinations (i.e., crop rotation systems) and their effects on soil nutrient pools. For annual potassium management technology, based on soil potassium release characteristics and crop potassium absorption patterns, potassium should be applied primarily to summer crops. However, the specific potassium allocation ratio for different crop seasons requires more field experimental data support.

3.4 Focusing on Deeper Soil Layer Properties Beyond Surface Effects

Current soil potassium pool research mostly focuses on the surface 0-20 cm layer, which is appropriate when soil potassium pools are not critically depleted. However, studies show significant surface accumulation and stratification effects of soil available potassium in some regions, with severe depletion in the 15-30 cm layer already below critical deficiency thresholds [56]. Our 2015 survey of major rotation systems in the North China Plain also showed that available potassium below 10 cm in wheat-maize and wheat-peanut rotations, and below 20 cm in wheat-maize, wheat-peanut, and wheat-cotton rotations, was below 100 mg • kg ^{1} (unpublished data, 2016). Therefore, from a long-term perspective, as potassium pools become depleted, deeper and layered monitoring of potassium pool dynamics and research on relationships between different soil depths and plant root systems are necessary to achieve matching between soil potassium supply and plant potassium absorption.

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Note: Figure translations are in progress. See original paper for figures.