

Changes in soil potassium and environmental impacts in the Yangtze River basin in China over the past 30 years

Dandan Zhu¹, Zhihong Li¹, Lixuan Guo¹, Jianwei Lu¹, Rihuan Cong², Tao Ren², and Xiaokun Li¹

¹Huazhong Agricultural University

²Huazhong Agriculture University

August 14, 2020

Abstract

The Yangtze River basin is distributed across subtropical monsoon climate regions, and has four seasons, including a hot rainy season. These climatic conditions provide favorable conditions for paddy-upland rotation. This paper summarizes the spatiotemporal changes in soil potassium (K) and K cycles in soil-plant systems, as well as environmental impacts on K changes, and provides information for optimal K management. During the past 30 years, soil available K increased by -7.1% to 103.4%. The increase was lower in Hunan, Guizhou, Zhejiang, and Jiangsu provinces (<10%) and higher in Anhui, Jiangxi, Henan, and Chongqing provinces (>30%), demonstrating that soil K pools were enhanced. Farm manure was gradually replaced by synthetic K sources, such as straw and mineral fertilizers, which contributed to an increase in crop yields and soil available K. The meta-analysis results showed that comprehensive K management strategies increased crop yield and soil available K by 11.0% and 44.3%, respectively, on average. Other factors such as balanced fertilization, recycling of straw, increase in atmospheric deposition, decrease in leaching, runoff, and soil K fixation also greatly influenced soil K changes, leading to improvements in crop yields, soil structure, soil fertility, and nutrient availability. Positive K cycles and appropriate K fertilizer use will facilitate proper K management, including cycling of straw, improving machinery and equipment, and estimating the optimal K fertilizer dose after straw. Future studies should focus on tradeoffs between different forms of K under various environmental conditions and accurate estimates of reductions in mineral-K fertilizer requirements following straw return.

1 Introduction

The Yangtze River basin, comprises approximately one-fifth of China's land area, and is the most important base of grain production. It is distributed across subtropical-monsoon climate regions with four seasons, including a hot rainy season. Annual precipitation ranges from 400 mm to 2590 mm, with half occurring during summer as high intensity storms that result in drying and wetting cycles. The annual temperature ranges from -4 °C to 20 °C, and the highest and the lowest temperatures occur in June to August and December to the following February, respectively. This climate provides favorable conditions for paddy-upland crop rotation systems. Paddy-upland rotation refers to planting rice and upland crops in the same field. Upland crops, including rape, wheat, peanuts, cotton, and potatoes, are planted in the dry season from October to the next April, while rice is planted in April to October. In the Yangtze River basin, rice-rape and rice-wheat are the most vital cropping systems, accounting for 51.3% of the total rice yield (Zhang et al., 2013) and more than 90% of the total rapeseed production (Ren et al., 2013).

The soils of the Yangtze River basin are characterized by low organic matter and acidic pH, with moderate levels of phosphorus and potential deficiency of available potassium (K). In fact, three-fourths of paddy soils in China are deficient in K (Rengel & Damon, 2008; Römheld & Kirkby, 2010). The main reasons for K deficiency are biomass removal from the soil in the form of grain, straw, or hay (Smil, 1999) and unbalanced

K fertilizer application (Cong et al., 2016). Leaching and runoff of K also contribute to decreased soil K (Rengel & Damon, 2008). Under highly intensive cropping systems and drying and wetting cycles, soil K is transformed between four forms, namely solution K, exchangeable K, nonexchangeable K, and structural K (Sparks, 1987). Soil K has changed greatly over the past 30 years due to changes in planting conditions. The Chinese national soil testing and fertilizer recommendation program, started in 2005, has been widely used in practice, and the recommended fertilizer rates have improved soil nutrient contents. Additionally, K cycles in plant-soil systems have changed because of environmental impacts, including balanced fertilization, recycling of straw, increased of atmospheric deposition, and decreased of soil K fixation. This paper summarizes changes in soil K and environmental impacts in the Yangtze River basin in China over the past 30 years, aiming at providing information for optimal K management in agricultural systems.

2 Materials and Methods

2.1 Literature search

We considered all articles returned by a search using the Web of Science and the China National Knowledge Infrastructure return with the following terms: [topic* AND (potassium OR straw return OR residue cycle) AND (soil potassium fertility OR soil available OR potassium balance OR potassium-bearing minerals OR yield) AND (rice OR wheat OR winter oilseed rape)]. All papers were published between January 1990 and June 2019. The search was limited to the following principles: all tests were conducted under field conditions, all fertilizer inputs were from simple chemical fertilizers, and the planting mode was single cropping or rotation cropping in the Yangtze River basin. After sorting, we obtained 55 papers representing 215 cases for rice, 157 for wheat, and 95 for winter oilseed rape (Table S1). Another 227 cases for soil available K content in different K management strategies were collected for a meta-analysis (Table S2). Finally, datasets for soil available K during the period 2007-2008 were compiled from the Chinese national soil testing and fertilizer recommendation program database.

2.2 Soil sampling and analysis

All 228 soil samples (10 cores per site) were collected for soil K distribution from the top 20 cm of the soil profile at all sites after crop harvest in the Yangtze River basin in China during 2018-2019. All samples were air dried and crushed to pass through 1 mm sieve for chemical analysis. Soil available K was measured using NH_4OAc extraction and a flame photometer method (Jackson, 1958).

2.3 Data analysis

ArcGIS 10.2 software was used to map soil K distribution. A meta-analysis using MetaWin 2.1 was conducted to assess the effects of K fertilization, straw return, and concurrent use both practices on crop yields and soil K content. Statistical analyses were performed to evaluate the range of variability and standard deviation (S.D.) using SPSS 18.0. All figures were drawn using Origin 8.0.

3 Results and Discussion

3.1 Spatiotemporal changes in soil K in the Yangtze River basin in China

Soil available K presents soil K concentration in real time, and it has been widely used to predict soil K availability and guide fertilization (Islam & Muttaleb, 2016). During 1990-2008 and 2009-2019, soil available K was $62.5\text{-}186.0 \text{ mg kg}^{-1}$ (mean, 96.8) and $35.9\text{-}373.5 \text{ mg kg}^{-1}$ (mean, 117.8), respectively, across the Yangtze River basin (Figure 1 and Table 1). Levels of soil available K increased by -7.1%-103.4%, the increase was lower in Hunan, Guizhou, Zhejiang and Jiangsu provinces ($< 10\%$), and higher in Anhui, Jiangxi, Henan and Chongqing provinces ($> 30\%$). Soil available K in 2009-2019 was greatly improved compared with that in 1990-2008.

3.2 K cycles in soil-plant systems

K is the seventh-most abundant element in the Earth's crust and the second-most abundant nutrient in leaves. Askegaard, Eriksen & Johnston (2004) reported that K concentrations range from 0.4- 4.3% and

vary widely with plant species, year, and fertilizer input. Similarly, appropriate K concentrations assist in plant photosynthesis, as well as plant resistance to drought, disease, and salt stress (Römheld & Kirkby, 2010; Malagoli, Britto, Schulze & Kronzucker, 2008; Zhang et al., 2018). The aim of K fertilization is to reduce crop growth restriction due to K deficiency. Previous studies have shown that K fertilizer application improves yields of rice, rapeseed, and wheat by 18.6%, 18.5%, and 17.1%, respectively, on average (Ren et al., 2013; Timsina, Kumar Singh & Majumdar, 2013).

K in soil is influenced by the tradeoffs between K input and output in soil-plant systems. Many studies have used K balance as a reflection of soil K (Singh, Singh & Damodar Reddy, 2002; Yu, Jiang, Zhou & Ma, 2008). During the past 30 years, soil K balance has been highly negative due to shortages of K input and large crop harvests (Sheldrick, Syers & Lingard, 2003). Thus, soil available K has increased due to the transformation of K from a nonexchangeable to an exchangeable state. A 31-year field experiment showed that insufficient K fertilizer application significantly changed soil quantity/intensity relationship, and caused depletion of different forms of K (Liao et al., 2017). Another 3-year experiment presented that soil K depletion firstly occurred in available K, then in slowly available K (Zhu, Lu, Cong, Ren & Li, 2019). Many studies indicated that without K fertilization, soil exchangeable and nonexchangeable K pools were depleted, even with the presence of K-bearing minerals, since most of the K utilized by crops comes from the nonexchangeable portion in clay minerals (Andrist-Rangel, Simonsson, Andersson, Öborn & Hillier, 2006; Zhao et al., 2014), the ability of 2:1 clay minerals to fix or release K acts as a K reservoir in soils (Barré, Velde & Abbadie, 2007a; Barré, Velde, Fontaine, Catel & Abbadie, 2008). During the period 2006-2019, synthetic K sources, including K fertilizer, straw and manure, have greatly increased K input. Soil K balance is positive when K inputs exceed outputs.

Table 2 shows data for soil K balance, soil K content, and clay mineralogy from long-term K fertilizer experiments. In treatments with K and straw, small increases in soil available K were observed at all sites, which also showed balanced soil K. Lower center of gravity position (cg) values in treatments with K and straw indicated that illitization of interstratified illite/smectite clay populations increased with K addition. Conversely, higher cg values showed that smectitization interstratified illite/smectite clay populations decreased with K depletion (Barré, Velde, Fontaine, Catel & Abbadie, 2008). K cycles in soil-plant systems is shown in Figure 2. Crop uptake and environmental loss are the main fates of fertilizer K. Optimal K management should aim to balance K application and crop uptake, and minimize environmental loss while enhancing crop yields.

3.3 Environmental impacts of K changes

3.3.1 Balanced fertilization

Balanced fertilization of low-fertility soils presents a significant challenge to agriculture. Inputs of K fertilizer and its proportion in macroelement fertilizers used in agriculture are shown in Figure 3. K fertilizer input increased continuously from 1990 to 2005. Since then, inputs have plateaued. Over the same time period, the proportion of K fertilizer to total fertilizer input increased continuously from 11.2% to 31.3%. However, during the period 1990-2005, trend of little or no use of K has become increasing common. A county-wide survey in the Yangtze Delta Region by Zhao et al. (2008) found that 38% of samples had K values below recommended levels. Since 2005, the Chinese government has conducted soil testing and developed fertilization technologies, resulting in application of fertilizer based on crop demands and soil supplying capacity. This has greatly improved soil K fertility in China (He et al., 2015). Additionally, the application of K has improved nitrogen and phosphorous use efficiency, increased nutrient uptake by crops, and further enhanced crop yields (Shukla, Yadav, Singh & Singh, 2009; Tan, Jin, Jiang, Huang & Liu, 2012; Timsina, Kumar Singh & Majumdar, 2013).

A meta-analysis of crop yield responses to different K managements, using no K fertilizer application as the baseline indicated that K fertilization, straw return, and concurrent use of both practices increased crop yields (Figure 4). The results indicated that K fertilization had positive effects on all crops, rice, wheat, and rape yields increased by 10.8%, 17.4% and 9.5%, respectively (9.9% on average). Another meta-analysis

evaluated the effects of different K managements on soil available K content both for one year and several years. Comprehensive K management strategies had positive effects on soil available K (42.5% on average; Figure 5). The increase in K fertilization after years of cultivation (49.8%) was 207.4% higher than that for one year (16.2%).

3.3.2 Recycling of straw

Straw has been removed from cropland for livestock or as fuel, a trend that was difficult to reverse before 2005. However, with recent increases in the exploitation of coal, petroleum, and natural gas and the development of industrial feed, farmers have become accustomed to using new fuels rather than straw, which has made it possible to return straw to croplands. Straw return increased rice, wheat, and oilseed rape yields by 6.5%, 7.4%, and 8.4% respectively, and had positive effects on soil available K (23.8% on average; Figure 4). Increases in soil available K after several years of straw return (29.7%) were 403.3% greater than those for one year (5.9%). Furthermore, K fertilization and straw return together had even greater improvement on crop yields and soil available K; rice, wheat, and rape yields increased by 15.5%, 26.9%, and 13.1%, respectively (16.3% on average for all crops), while soil available K increased by 66.4%. Increases in soil available K after several years of cultivation under K fertilization and straw return (82.0%) were 720.0% greater than those for one year (10.0%).

Straw return is the best strategy for improving soil structure, as it increases soil organic matter fractions and aggregate fractions, decreases soil bulk density, improves soil C, N, K stocks and nutrients availability (Singh, Jalota & Singh, 2007; Guo & Wang, 2013; Qiu et al., 2014; Wang et al., 2015; Yu et al., 2016; Zhao et al., 2018). Furthermore, High rates of straw return changed microbial community structure and promoted soil microbial activity (Zhao et al., 2016), as well as microbial communities (Pu, Zhang, Zhang, Liu & Zhang, 2016; Chen et al., 2017; Chen et al., 2017).

3.3.3 Increase of atmospheric deposition

The availability of K in ecosystems also depends on K inputs via atmospheric deposition, which can originate both through natural processes and human and agricultural activities, such as energy production, transportation, construction-materials production and fertilization (Walker, Young, Crittenden & Zhang, 2003; Urban et al., 2012). Golobocanin, Zujic, Milenkovic & Miljevic (2009) demonstrated that human activities contribute a higher proportion of atmospheric deposition than natural processes. Jordi & Josep (2015) indicated that current levels of K fertilization and atmospheric deposition of K (0.066×10^9 t year⁻¹) are very low compared with global available soil K (57.7×10^9 t). However, in intensive cropping systems, 4.4-8.2 kg K ha⁻¹ of wet deposition has been reported in some areas of China (Li & Jin, 2011).

3.3.4 Decrease of soil K fixation

The 2:1 clay minerals play a key role in the soil K cycle (Arkcoll, Goulding & Hughes, 1985; Hinsinger, 2002). K⁺ trapped in 2:1 clay mineral interlayer sites and defined as nonexchangeable based on classical agronomical tests is available to plants to some extent (Mortland, Lawton & Uehara, 1956; Tributh, Boguslawski, Lieres, Steffens & Mengel, 1987; Hinsinger, Jaillard & Dufey, 1992). Soil wetting and drying cycles significantly affect soil K fixation (Zörb, Senbayram & Peiter, 2014). In soils with high cation-exchange capacity, wetting and drying cycles increase soil K fixation (Shakeri & Abtahi, 2019). Soil K fixation also depends on the K concentration in the soil solution (Schneider, Tesileanu, Charles & Sinaj, 2013). Restricting input of K may deplete soil K fertility, thereby exhausting interlayer K (Mengel & Kirkby, 2001). As interlayer K is depleted, soil K fixation capacity increases. In K-deficient soils, or in soils poor in K-rich minerals, K fixation occurs due to the transfer of K⁺ from the soil solution to the specific sites of the 2:1 interlayer, causing their collapse (Portela, Monteiro, Fonseca & Abreu, 2019). Simonsson, Hillier & Öborn (2009) showed that the balance between K output and input greatly influenced soil K fixation capacity. Soils with long-term K application had lower capacity to fix K compared to those without K treatment (Tan, Liu, Jiang, Luo & Li, 2017). Soil K fixation capacity could be reduced after soil K pools are replenished, thus increasing the availability of fertilizer K, which would benefit virtuous cycling of soil K pools.

3.3.5 Reduction of leaching and runoff loss

K in soil becomes unusable by plants due to limitation in spatial availability caused by runoff and leaching loss. This is critical for maintaining soil fertility to reducing environmental loss. Preferential flow plays a role in the initial movement of K to depth after a urination event (Kayser & Isselstein, 2005). A previous study found that Losses of K by leaching occurred primarily due to macropore flow of urine below the main rooting depth (Williams, Gregg & Hedley, 1990). Spikes in nutrient losses frequently occurred following intense rainfall rather than dry season, especially when coinciding with fertilization events (Erickson, Cisar, Snyder & Volin, 2005). Over irrigation can increase risk of soil leaching and runoff. Ma (2004) indicated that shallow-wet irrigation had higher water use efficiency and less nutrition loss compared with full-wet irrigation and dry irrigation. This irrigation mode would be appropriate for sustainable development. Additionally, soil tillage systems significantly influenced soil K loss. Soluble K concentrations in runoff water decreased exponentially from the first to the fifth simulated rainfall test in no-till treatments, whereas this decrease was linear and less evident in the conventional tillage treatment (Bertol, Engel, Mafra, Bertol & Ritter, 2007). Under the paddy-upland cropping system in the Yangtze River basin in China, wet and dry periods alternate frequently, and unreasonable irrigation would cause a loss of nutrients, especially during the wet season. Over the past 15 years, irrigation, soil tillage management, and correct fertilizer application timing have improved, reducing the risk of nutrient loss.

4Future perspectives and conclusions

4.1 Proper K cycles in agricultural systems

China's agricultural system urgently requires efficient exploitation of existing K resources and realization of a virtuous cycle for K. Global K use efficiency for cereal production is only 19% (Dhillon, Eickhoff, Mullen & Raun, 2019), mainly due to the complete removal of crop residue. Approximately 80% of K removed from the soil is retained in nongrain crop residues (Ren et al., 2013; Singh et al., 2018). Improved returns of crop residue aids in K cycling in agricultural systems. However, approaches to and effects of straw return and competition with crops for nitrogen during straw ripening, seeding and the nutrition absorption require further study. Reducing the risk of K leaching and runoff loss will have a positive impact on the virtuous cycle of the soil K reservoir. However, environmental K losses have received less attention. Virtuous cycles for K can be realized in agricultural systems by advocating cycles of straw return, developing straw-returning technology, and improve the machinery and equipment measures that support straw return.

4.2 Proper use of K fertilizer

There is a regional imbalance of K input in the Yangtze River basin, and a large proportion of K fertilizer used in agriculture is imported. Imbalanced fertilizer use leads to balance surplus of soil N and P but a serious depletion of K (Zhen, Zoenisch, Chen & Feng, 2006). K fertilizer application rates have increased dramatically (by 419%) over the past 30 years, although much of the soil in the Yangtze River basin is still potentially deficient in K and the soil K pools are hard to maintain under intensive cropping regimes (He et al., 2015). Therefore, under condition of high-yield, high-quality, and high-efficiency crop production, appropriate K input should be considered for the maintenance and improvement of soil K fertility. Appropriate K fertilization should take into account crop needs, soil supply, and environmental losses, as well as fertilizer varieties and the rate, timing, and location of applications. Inputs of crop residues K also need to be considered to estimate the potential reductions mineral K fertilizer application when using straw return, which will be essential for K management of these rotation systems.

4.3 Conclusions

Over the past 30 years, soil K pools have replenished, and soil available K increased -7.1%-103.4% across the Yangtze River basin. These changes were closely related to the changes of agricultural production conditions as follows: balanced fertilization, including partial application of N fertilizer and balanced application of NPK fertilizer; straw return, which return 80% of the total K taken away by harvest, thus greatly alleviates soil K deficiency; increased soil K input due to atmospheric deposition and the increase of drying and wetting

deposition; reduction in soil K fixation; and reduction of the leaching and runoff loss in soil K pools. Although soil K pools have been improved in the Yangtze River basin in China over the past 30 years, the soil remains in potentially K-deficient state. Realization of virtuous K cycles in plant-soil system remains a challenge in China, as does how to determine the appropriate rate for achieving target yields and improving plant resistance. It is also important to strengthen relevant support measures in practice. Further improvement in plant-soil K cycles will be realized in the future in Yangtze River basin in China.

ACKNOWLEDGEMENTS

We thank the National Natural Science Foundation of China (41571284) and the National Key Research and Development Program of China (2016YFD0200108) for providing funding for this study.

ORCID

Dan-Dan Zhu <https://orcid.org/0000-0003-0279-082X>

Xiao-Kun Li <https://orcid.org/0000-0001-5643-2919>

REFERENCES

- Andrist-Rangel, Y., Simonsson, M., Andersson, S., Öborn, I., & Hillier, S. (2006). Mineralogical budgeting of potassium in soil: A basis for understanding standard measures of reserve potassium. *Journal of Plant Nutrition and Soil Science* , 169, 605–615. <https://doi.org/10.1002/jpln.200621972>
- Arkcoll, D. B., Goulding, K. B. T., & Hughes, J. C. (1985). Traces of 2:1 layer silicate clays in oxisols from Brazil and their significance for potassium nutrition. *Journal of Soil Science* , 36, 123–128. <https://doi.org/10.1111/j.1365-2389.1985.tb00317.x>
- Askegaard, M., Eriksen, J., & Johnston, A. E. (2004). Sustainable management of potassium. In: Schjorring P, Elmholt S, Christensen BT. (Eds.). *Managing soil quality: challenges in modern agriculture*. Wallingford: CABI Publishing, pp. 85–102.
- Barré, P., Velde, B., Fontaine, C., Catel, N., & Abbadie, L. (2008). Which 2:1 clay minerals are involved in the soil potassium reservoir? Insights from potassium addition or removal experiments on three temperate grassland soil clay assemblages. *Geoderma* , 146, 216–223. <https://doi.org/10.1016/j.geoderma.2008.05.022>
- Barré, P., Velde, B., & Abbadie, L. (2007a). Dynamic role of “illite-like” clay minerals: in temperate soils: facts and hypotheses. *Biogeochemistry* , 82, 77–88. <https://doi.org/10.1007/s10533-006-9054-2>
- Bertol, I., Engel, F. L., Mafra, A. L., Bertol, O. J., & Ritter, S. R. (2007). Phosphorus, potassium and organic carbon concentrations in runoff water and sediments under different soil tillage systems during soybean growth. *Soil & Tillage Research* , 94, 142–150. <https://doi.org/10.1016/j.still.2006.07.008>
- Chen, Z., Wang, H., Liu, X., Zhao, X., Lu, D., Zhou, J., & Li, C. (2017). Changes in soil microbial community and organic carbon fractions under short-term straw return in a rice–wheat cropping system. *Soil & Tillage Research* , 165: 121–127. <https://doi.org/10.1016/j.still.2016.07.018>
- Cong, R., Li, H., Zhang, Z., Ren, T., Li, X. & Lu, J. (2016). Evaluate regional potassium fertilization strategy of winter oilseed rape under intensive cropping systems: Large-scale field experiment analysis. *Field Crops Research* , 193, 34–42. <https://doi.org/10.1016/j.fcr.2016.03.004>
- Dhillon, J. S., Eickhoff, E. M., Mullen, R. W., & Raun, W. R. (2019). World potassium use efficiency in cereal crops. *Agronomy Journal* , 111, 889–896. <https://doi.org/10.2134/agronj2018.07.0462>
- Erickson, J. E., Cisar, J. L., Snyder, G. H., & Volin, J. C. (2005). Phosphorus and Potassium Leaching under Contrasting Residential Landscape Models Established on a Sandy Soil. *Crop Science* , 45, 546–552. <https://doi.org/10.2135/cropsci2004.0315er>

- Golobocanin, D., Zujic, A., Milenkovic, A., & Miljevic, N. (2009). Precipitation composition and wet deposition temporal pattern in Central Serbia for the period from 1998 to 2004. *Environmental Monitoring and Assessment* , 142, 185–198. <https://doi:10.1007/s10661-007-9919-4>
- Guo, Z., & Wang, D. Z. (2013). Long-term effects of returning wheat straw to croplands on soil compaction and nutrient availability under conventional tillage. *Plant Soil & Environment* , 59, 280–286. doi:10.17221/846/2012-PSE
- He, P., Yang, L., Xu, X., Zhao, S., Chen, F., Li, S., ... Adrian, M. J. (2015). Temporal and spatial variation of soil available potassium in China (1990–2012). *Field Crops Research* , 173, 49–56. <https://doi:10.1016/j.fcr.2015.01.003>
- Hinsinger, P. (2002). Potassium. In: Lal, R. (Eds.), *Encyclopedia of Soil Science*. Marcel Dekker, Inc., New-York, USA.
- Hinsinger, P., Jaillard, B., & Dufey, E. D. (1992). Rapid weathering of a trioctahedral mica by the roots of ryegrass. *Soil Science Society of America Journal* , 56, 977–982. <https://doi:10.2136/sssaj1992.03615995005600030>
- Islam, A., & Muttaleb, A. (2016). Effect of potassium fertilization on yield and potassium nutrition of Bo&ro rice in a wetland ecosystem of Bangladesh. *Archives of Agronomy and Soil Science* , 62, 1530–1540. <https://doi:10.1080/03650340.2016.1157259>
- Jackson, M.L. (1958). *Soil Chemical Analysis*. Prentice Hall, Englewood Cliffs, NJ.
- Kayser, M., & Isselstein, J. (2005). Potassium cycling and losses in grassland systems: A review. *Grass & Forage Science* , 60, 213–224. <https://doi:10.1111/j.1365-2494.2005.00478.x>
- Lawlor, D. W. (2004). Principles of plant nutrition. In: Mengel K, Kirkby EA. (Eds.), *Annals of Botany*, pp, 479–480.
- Li, S., & Jin, J. (2011). Characteristics of Nutrient Input/Output and Nutrient Balance in Different Regions of China. *Scientia Agricultura Sinica* , 44, 4207–4229. (In Chinese with English abstract)
- Liao, Y. L., Lu, Y. H., Xie, J., Nie, J., Yang, Z. P., & Zhou, X. (2017). Effects of Long-term Application of Chemical Potassium Fertilizer and Incorporation of Rice Straw on Potassium Supplying Capacity of Red Soil in Double Cropping Paddy Field. *Acta Pedologica Sinica* , 54, 456–466. (In Chinese with English Abstract)
- Ma, H. L. (2004). Investigation on the effect of controlling the non-point source pollution by shallow wet irrigation. Master Thesis, Nanjing Forestry University, China.
- Malagoli, P., Britto, D. T., Schulze, L. M., & Kronzucker, H. J. (2008). Futile Na⁺ cycling at the root plasma membrane in rice (*Oryza sativa* L.): kinetics, energetics, and relationship to salinity tolerance. *Journal of Experimental Botany* , 59, 4109–4117. <https://doi:10.1093/jxb/ern249>
- Mortland, M. M., Lawton, K., & Uehara, G. (1956). Alteration of biotite to vermiculite by plant growth. *Soil Science* , 82, 477–481. <https://doi:10.1097/00010694-195612000-00004>
- Portela, E., Monteiro, F., Fonseca, M., & Abreu, M. M. (2019). Effect of soil mineralogy on potassium fixation in soils developed on different parent material. *Geoderma* , 343, 226–234. <https://doi:10.1016/j.geoderma.2019.02.040>
- Pu, X. Z., Zhang, G.J., Zhang, P. P., Liu, Y. J., & Zhang, W. F. (2016). Effects of straw management, inorganic fertilizer, and manure amendment on soil microbial properties, nutrient availability, and root growth in a drip-irrigated cotton field. *Crop & Pasture Science*, 67, 1297–1308. <https://doi:10.1071/cp16230>
- Qiu, S., J, Xie, J. G., Zhao, S. C., Xu, X. P., Hou, Y. P., Wang, X. F., ... Jin, J. Y. (2014). Long-term effects of potassium fertilization on yield, efficiency, and soil fertility status in a rain-fed maize system in northeast China. *Field Crops Research* , 163: 1–9. <https://doi:10.1016/j.fcr.2014.04.016>

- Ren, T., Lu, J., Li, H., Zou, J., Xu, H., Liu, X., & Li, X. (2013). Potassium-fertilizer management in winter oilseed-rape production in China. *Journal of Plant Nutrition and Soil Science*, 176, 429-440. <https://doi.org/10.1002/jpln.201200257>
- Rengel, Z., & Damon, P. M. (2008). Crops and genotypes differ in efficiency of potassium uptake and use. *Physiologia Plantarum*, 133, 624-636. <https://doi.org/10.1111/j.1399-3054.2008.01079.x>
- Romheld, V., & Kirkby, E. A. (2010). Research on potassium in agriculture: needs and prospects. *Plant and Soil*, 335, 155-80. <https://doi.org/10.1007/s11104-010-0520-1>
- Sardans, J. & Penuelas, J. (2015). Potassium: a neglected nutrient in global change. *Global Ecology and Biogeography*, 24, 261-275. <https://doi.org/10.1111/geb.12259>
- Schneider, A., Tesileanu, R., Charles, R., & Sinaj, S. (2013). Kinetics of Soil Potassium Sorption-Desorption and Fixation. *Communications in Soil Science and Plant Analysis*, 44, 837-849. <https://doi.org/10.1080/00103624.2013.749442>
- Shakeri, S., & Abtahi, A. (2019). Potassium fixation capacity of some highly calcareous soils as a function of clay minerals and alternately wetting-drying. *Archives of Agronomy and Soil Science*, 66: 445-457. <https://doi.org/10.1080/03650340.2019.1619176>
- Sheldrick, W. F., Syers, J. K., & Lingard, J. (2003). Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agriculture Ecosystems and Environment*, 94, 341-354. [https://doi.org/10.1016/s0167-8809\(02\)00038-5](https://doi.org/10.1016/s0167-8809(02)00038-5)
- Shukla, S. K., Yadav, R. L., Singh, P. N., & Singh, I. (2009). Potassium nutrition for improving stubble bud sprouting, dry matter partitioning, nutrient uptake and winter initiated sugarcane (*Saccharum* spp. hybrid complex) ratoon yield. *European Journal of Agronomy*, 30, 27-33. <https://doi.org/10.1016/j.eja.2008.06.005>
- Simonsson, M., Hillier, S., & Oborn, I. (2009). Changes in clay minerals and potassium fixation capacity as a result of release and fixation of potassium in long-term field experiments. *Geoderma*, 151, 109-120. <https://doi.org/10.1016/j.geoderma.2009.03.018>
- Singh, G., Jalota, S. K., & Singh, Y. (2007). Manuring and residue management effects on physical properties of a soil under the rice-wheat system in Punjab, India. *Soil & Tillage Research*, 94, 229-238. <https://doi.org/10.1016/j.still.2006.07.020>
- Singh, M., Singh, V., & Damodar Reddy, D. (2002). Potassium balance and release kinetics under continuous rice-wheat cropping system in Vertisol. *Field Crops Research*, 77, 81-91. [https://doi.org/10.1016/s0378-4290\(01\)00206-4](https://doi.org/10.1016/s0378-4290(01)00206-4)
- Singh, V. K., Dwivedi, B. S., Yadvinder-Singh, Singh, S. K., Mishra, R. P., Shukla, A. K., ... Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice-maize system in north-western India. *Field Crops Research*, 224, 1-12. <https://doi.org/10.1016/j.fcr.2018.04.012>
- Smil, V. (1999). Crop Residues: Agriculture's Largest Harvest. *BioScience*, 49, 299-308. <https://doi.org/10.2307/1313613>
- Sparks, D. L. (1987). Potassium dynamics in soil. In: B.A. Stewart, (Eds), *Advances in soil science*. Springer, New York. pp. 1-63.
- Sun, H. X., Wang, H. Y., Zhou, J. M., Du, C. W., Chen, X. Q., Qin, S. W. (2009). Change of soil potassium fertility in long-term located field experiment and comparison of different methods to measure potassium change in soil. *Soils*, 41, 212-217. (In Chinese with English Abstract)
- Tan, D., Liu, Z., Jiang, L., Luo, J., & Li, J. (2017). Long-term potash application and wheat straw return reduced soil potassium fixation and affected crop yields in North China. *Nutrient Cycling in Agroecosystems*, 108, 121-133. <https://doi.org/10.1007/s10705-017-9843-0>

- Tan, D., Jin, J., Jiang, L., Huang, S., & Liu, Z. (2012). Potassium assessment of grain producing soils in North China. *Agriculture, Ecosystems & Environment* , 148, 65–71. <https://doi.org/10.1016/j.agee.2011.11.016>
- Timsina, J., Kumar Singh, V., & Majumdar, K. (2013). Potassium management in rice-maize systems in South Asia. *Journal of Plant Nutrition and Soil Science* , 176, 317–330. <https://doi.org/10.1002/jpln.201200253>
- Tributh, H., Boguslawski, E. V., Lieres, A. V., Steffens, D., & Mengel, K. (1987). Effect of potassium removal by crops on transformation of Illitic clay minerals. *Soil Science* , 143, 404–409. <https://doi.org/10.1097/00010694-198706000-00003>
- Urban, R. C., Lima-Souza, M., Caetano-Silva, L., Queiroz, M. E. C., Nogueira, R. F. P., Allen, A. G., ... Campos, M. L. A. M. (2012). Use of levoglucosan, potassium, and water-soluble organic carbon to characterize the origins of biomass-burning aerosols. *Atmospheric Environment* , 61, 562–569. <https://doi.org/10.1016/j.atmosenv.2012.07.082>
- Walker, T., Young, S., Crittenden, P., & Zhang, H. (2003). Anthropogenic metal enrichment of snow and soil in north-eastern European Russia. *Environmental Pollution* , 121, 11–21. [https://doi.org/10.1016/s0269-7491\(02\)00212-9](https://doi.org/10.1016/s0269-7491(02)00212-9)
- Wang, J., Wang, X., Xu, M., Feng, G., Zhang, W., & Lu, C. (2015). Crop yield and soil organic matter after long-term straw return to soil in China. *Nutrient Cycling in Agroecosystems* , 102, 371–381. <https://doi.org/10.1007/s10705-015-9710-9>
- Williams, P. H., Gregg, P. E. H., & Hedley, M. J. (1990). Use of potassium bromide solutions to simulate dairy cow urine flow and retention in pasture soils. *New Zealand Journal of Agricultural Research* , 33, 489–495. <https://doi.org/10.1080/00288233.1990.10428447>
- Xiong, M. B., Shu, F., Song, G. Y., Shi, X. J., Mao, Z. Y. (2003). Effects of long-term potassium application on yield and soil potassium in rice-wheat systems in purple soil. *Acta Pedologica Sinica* , 40, 274–279. (In Chinese with English Abstract)
- Yu, W. T., Jiang, Z. S., Zhou, H., & Ma, Q. (2008). Effects of nutrient cycling on grain yields and potassium balance. *Nutrient Cycling in Agroecosystems* , 84, 203–213. <https://doi.org/10.1007/s10705-008-9237-4>
- Yu, C., Wang, X., Hu, B., Yang, C., Sui, N., Liu, R., ... Zhou, Z. (2016). Effects of wheat straw incorporation in cotton-wheat double cropping system on nutrient status and growth in cotton. *Field Crops Research* , 197, 39–51. <https://doi.org/10.1016/j.fcr.2016.08.003>
- Zhang, H., Chen, T., Liu, L., Wang, Z., Yang, J., & Zhang, J. (2013). Performance in Grain Yield and Physiological Traits of Rice in the Yangtze River Basin of China During the Last 60 yr. *Journal of Integrative Agriculture* , 12, 57–66. [https://doi.org/10.1016/s2095-3119\(13\)60205-1](https://doi.org/10.1016/s2095-3119(13)60205-1)
- Zhang, J., Lu, Z., Pan, Y., Ren, T., Cong, R., Lu, J., & Li, X. (2018). Potassium deficiency aggravates yield loss in rice by restricting the translocation of non-structural carbohydrates under Sarocladium oryzae infection condition. *Physiologia Plantarum*, 167, 352–364. <https://doi.org/10.1111/ppl.12896>
- Zhao, H., Shar, A. G., Li, S., Chen, Y., Shi, J., Zhang, X., & Tian, X. (2018). Effect of straw return mode on soil aggregation and aggregate carbon content in an annual maize-wheat double cropping system. *Soil & Tillage Research*, 175, 178–186. <https://doi.org/10.1016/j.still.2017.09.012>
- Zhao, S., He, P., Qiu, S., Jia, L., Liu, M., Jin, J., & Johnston, A. M. (2014). Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. *Field Crops Research* , 169, 116–122. <https://doi.org/10.1016/j.fcr.2014.09.017>
- Zhao, S., Li, K., Zhou, W., Qiu, S., Huang, S., & He, P. (2016). Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in north-central China. *Agriculture, Ecosystems & Environment*, 216, 82–88. <https://doi.org/10.1016/j.agee.2015.09.028>

Zhao, Y., Xu, X., Darilek, J. L., Huang, B., Sun, W., & Shi, X. (2008). Spatial variability assessment of soil nutrients in an intense agricultural area, a case study of Rugao County in Yangtze River Delta Region, China. *Environmental Geology* , 57, 1089–1102. <https://doi.org/10.1007/s00254-008-1399-5>

Zhen, L., Zebisch, M. A., Chen, G., & Feng, Z. (2006). Sustainability of farmers' soil fertility management practices: A case study in the North China Plain. *Journal of Environmental Management* , 79, 409–419. <https://doi.org/10.1016/j.jenvman.2005.08.009>

Zhu, D. D., Lu, J. W., Cong, R. H., Ten, T., & Li, X. K. (2019). Potassium management effects on quantity/intensity relationship of soil potassium under rice-oilseed rape rotation system. *Archives of Agronomy and Soil Science* , 1-14. <https://doi.org/10.1080/03650340.2019.1663830>

Zorb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture - Status and perspectives. *Journal of Plant Physiology* , 171, 656–669. <https://doi.org/10.1016/j.jplph.2013.08.008>

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

Figure Captions

FIGURE 1 Distribution of soil available K across the Yangtze River basin, China during 1990- 2008 and 2009-2019.

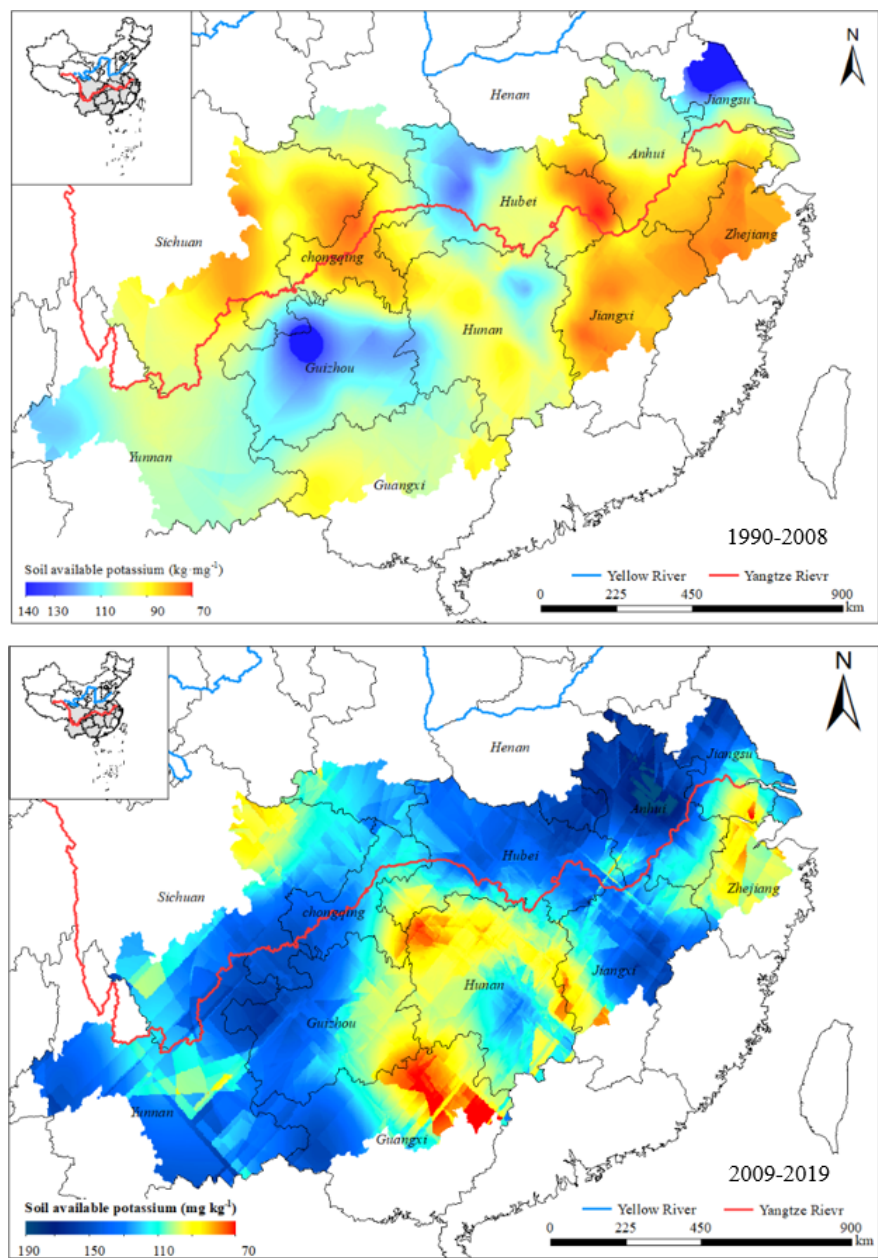


FIGURE 2 K cycles in soil-plant systems.

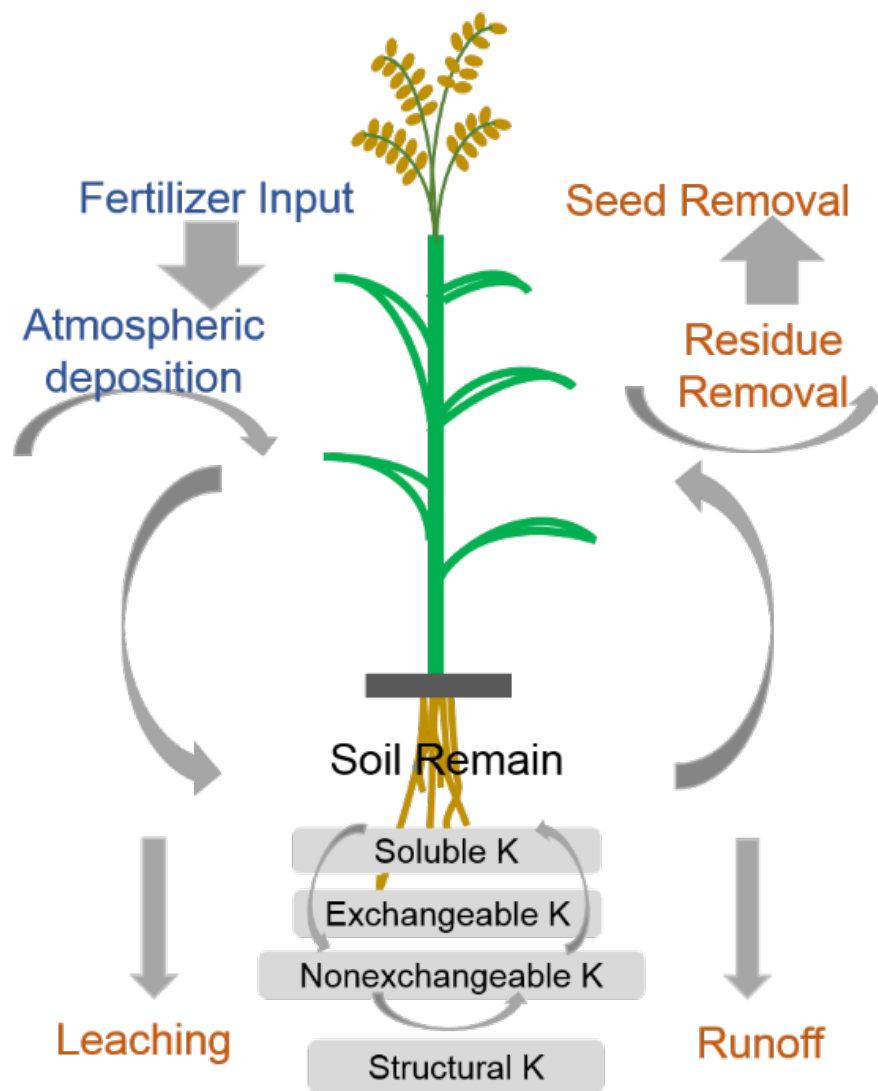


FIGURE 3 The inputs of K fertilizer and its proportion in macroelement fertilizers in agriculture from 1990 to 2018.

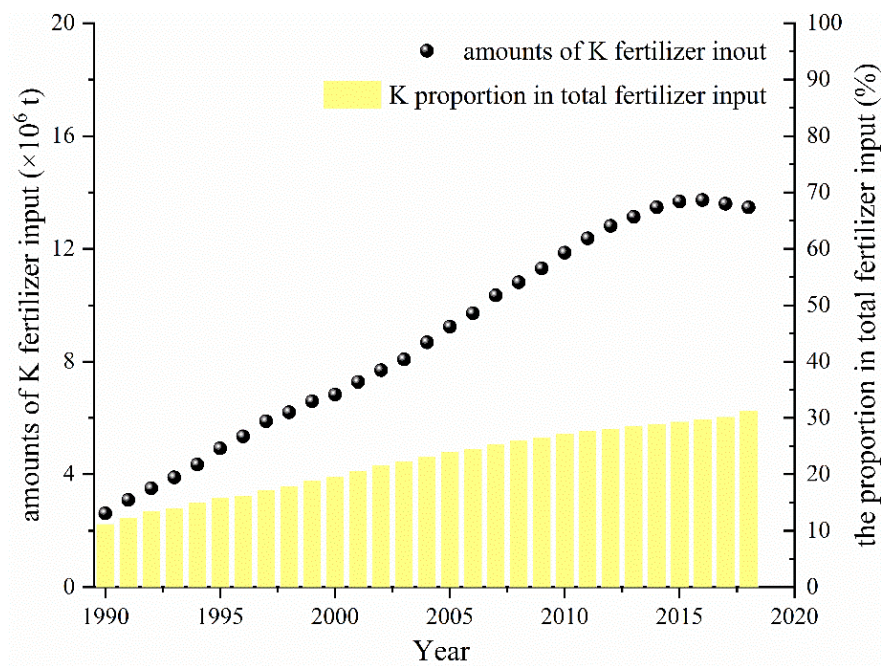
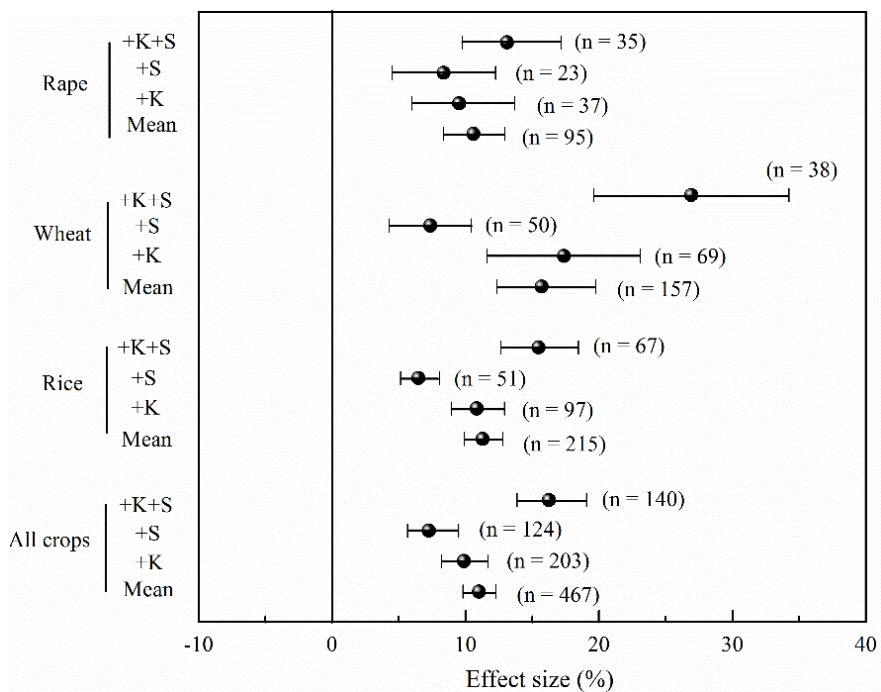


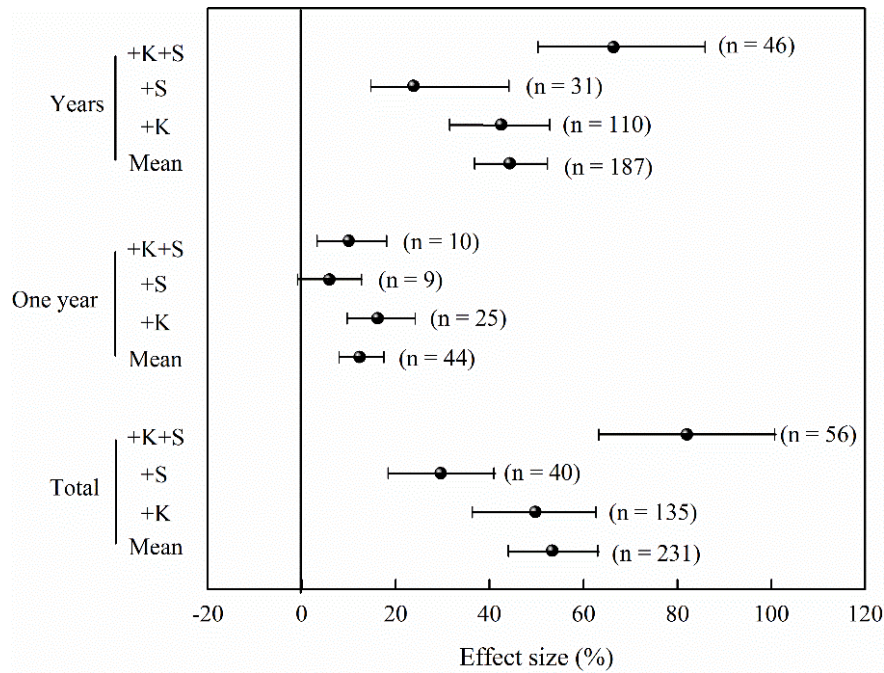
FIGURE 4 Effects of K fertilization, straw return, and concurrent use of both practices on the response to rice, wheat, and oilseed rape yields.



Note: Y-axis shows categories and number of datasets per category in brackets; X-axis shows effect size of fertilizer application to crop yields; Error bars indicated 95% confidence intervals.

FIGURE 5 Effects of K fertilization, straw return, and concurrent use of both practices on the response to

soil available K over time.



Note: Y-axis shows categories and number of datasets per category in brackets; X-axis shows effect size of fertilizer application to soil available K; Error bars indicates 95% confidence intervals.

TABLES

TABLE 1 Distribution of soil available K in the Yangtze River basin, China in 2008 and 2018.

Soil available K (mg kg ⁻¹)	2008 (n =228)	2018 (n=228)
Mean	96.8	118.0
Standard Error	21.7	62.5
Min	62.6	35.9
Max	186.0	373.5
Mid-value	84.2	103.6
lower quartiles	81.4	72.0
Upper quartiles	106.1	139.0

TABLE 2 Long-term effects of integrative K management strategies effects on soil K balance, soil K content, and clay mineralogy.

Site	Planting years	Rotation	Treatment	Total K balance	Soil available K	Clay mineralogy (cg value)	Reference
Chongqing	1991-2000	Rice-wheat	-K	-1686.6	56.0	—	(Xiong et al., 2003)
			+K	-712.9	84.2	—	
			+K+S	-12.2	88.1	—	

Site	Planting years	Rotation	Treatment	Total K balance	Soil available K	Clay mineralogy (cg value)	Reference
Henan	1989-2005	Maize- wheat	-K	-2352	59	—	(Sun et al., 2009)
			+K	513	275	—	
			+K+S	636	234	—	
Hubei	2014-2017	Rice-rape	-K	-780	51.4	1.12	(Zhu et al., 2019)
			+K	-894	62.8	1.11	
			+K+S	29	79.0	1.12	
Hunan	1981-2012	Rice-rice	-K	-3308	95	1.17	(Liao et al., 2017)
			+K	-607	159	1.15	
			+K+S	287	220	1.14	

Note: -K, no K fertilization; +K, K fertilization; +K+S, K fertilization and straw return; the value of cg was evaluated by the equation, $cg = \sum (a_i * pos_i) / \sum a_i$, a_i is the area of the peak i, pos_i is the position of the peak i.