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Negative potassium balances threaten global crop production

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Negative potassium balances threaten global crop production

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Abstract

The role of potassium (K) in global food security has been neglected compared with other plant nutrients. To evaluate global potassium (K) limitations on crop yields, we compiled an extensive multi-indicator database comprising 22 million soil samples, 66,300 K-fertilization yield trials, and 117,000 field-level input-output K balances. These data span 31 cropping systems that together account for two-thirds of global cereal, oilseed, and fiber production. We found that most soils cannot supply enough K to meet crop requirements without additional K inputs. Variation in K limitation across cropping systems was associated with soil properties, cropping intensity, K balance, and residue management. We observed negative K balances and significant yield responses to K fertilization in South Asia, Southeast Asia, and Africa, primarily driven by low K fertilizer use and large residue removal. Other cropping systems are moving towards a K limitation due to continuous cropping with inadequate K replenishment, as observed in the Latin American Pampas and Western U.S. Corn Belt. Our analysis indicates that sustaining current yields without further soil K mining would require a 30% increase in K inputs globally, while achieving attainable yields would require K fertilizer use to increase by nearly 70%, from 15.0 to 24.7 million metric tons annually. Meeting future food demand on existing cropland will require more attention to K management across major cropping systems to improve soil health and sustain or increase crop yields.

Main text

Potassium (K) is an essential plant mineral nutrient that plays a critical role in enzyme activation, water regulation, photosynthesis, carbohydrate mobilization, and stress tolerance in plants[1–3]. Indeed, the total amount of crop K uptake during the growing season is comparable to that of nitrogen (N), but larger than for other essential mineral nutrients such as phosphorus (P). Despite its importance, however, K has received less attention than the aforementioned nutrients[4–6]. For example, the number of published scientific articles on K in agricultural and biological sciences from 2004 to 2023 (*n* = 6858), is substantially lower than for N and P (*n* = 46728 and 17073, respectively)[1]. One reason is that many agricultural soils have evolved from K-rich parent material (e.g., micas) and can provide sufficient K to sustain acceptable yields without K fertilizer applications[7,8]. Furthermore, K losses from agro-ecosystems have fewer direct negative environmental impacts compared with N or P. Finally, K deficiencies frequently manifest without visual symptoms (i.e., 'hidden hunger'), and lead to smaller and less consistent yield losses than those for other nutrients, making the diagnosis of K limitation more challenging[9,10]. Collectively, these factors have led to neglecting the importance of K management for supporting high crop yields in many regions worldwide.

From a crop production perspective, K limitation occurs when K supply from soil, inorganic and organic fertilizers, and other sources such as seed and irrigation water is

[1] Based on a Scopus database search conducted in June 2024, restricted to articles classified under Agricultural and Biological Sciences.

123 insufficient to meet crop requirements. Drivers for K limitation could be associated with
124 both agronomic and soil factors. In this context, K balance is defined as the difference
125 between K inputs (fertilizers, irrigation water, and other sources) and outputs (K removal
126 in harvested products and residues). Continuous negative K balances, driven by K
127 removal without adequate replenishment over extended cropping periods, lead to soil K
128 depletion and reduced productivity. This effect is exacerbated when crop residues are
129 removed or burned because, unlike N and P, much of the K taken up by crops remains
130 in vegetative organs such as leaves and stems, with a smaller amount removed in the
131 harvested grain[11]. Alternatively, some soils have inherently low K supply as determined
132 by parental material, texture, mineralogy, and weathering[12,13]. While there have been
133 efforts to quantify the K limitation in natural ecosystems globally and to examine the
134 associated drivers[14], we are not aware of a comparable study for cropping systems that
135 integrates soil K status, crop response, and nutrient balance into a single framework[6].
136 Prior agronomic studies on K are limited to specific sites and/or crops and therefore do
137 not allow a robust global assessment[15–17]. Moreover, previous studies have limited
138 applicability nowadays because crop K removal depends on yield and crop residue
139 management, which, together with soil K supply, have changed substantially over time.
140 Hence, cropping systems that were not limited by K in the past may progressively
141 transition toward K limitation after decades of crop nutrient removal [9,18]. Assessing K
142 limitation is also vital from a geopolitical perspective because the main potash
143 producers are located in a few countries (mostly Canada, Russia, Belarus, the U.S.,
144 China, Germany, Israel, Jordan, and Laos), implying that trade disruptions could easily
145 affect global availability and prices of K fertilizer, as occurred in recent years[19,20]

Quantifying the extent and severity of the K limitation in agricultural systems is essential to assess where and how much K is needed for increasing crop production on existing cropland, while avoiding long-term soil nutrient depletion. Our working hypothesis is that most agricultural soils cannot meet crop K requirements and that current K inputs are not sufficient to avoid negative K balances and thus soil K depletion. To evaluate this hypothesis, we assessed the global K limitation to crop production using data from 22 million soil samples, 66,300 fertilizer trials, and 117,000 on-farm nutrient balances collected since 2000, following an approach that includes meta-analysis, spatial analysis, and process-based crop modelling **(see Methods)**. We categorized cropping systems according to their degree of K limitation and K balances and estimated future K requirements to maintain current crop yields or reach attainable yields without soil K mining. Implications for agricultural research and development (R&D) programs, market development, and policymakers are discussed.

Results

Soil K supply and crop yields

We focused on 31 cropping systems that collectively account for ca. two-thirds of global cereal, oilseed, and fiber production **(Extended Data Figs. 1-2; Supplementary Table S1)**. A cropping system can include different crop species and water regimes (e.g., western US Corn Belt). Cropland area varied across cropping systems, ranging from 1

168 million ha for lowland rice in the Latin American Pampas and the Red River delta in
169 Vietnam to ca. 35 million ha in the Brazilian Cerrado. Thus, cropping-system averages
170 were calculated by weighing the crop and water regime harvested areas within each
171 system and, when appropriate, variables were annualized by accounting for the
172 cropping intensity **(see Methods)**. Selected cropping systems covered a wide range of
173 yield, environmental conditions, and management practices, including K fertilizer
174 application and residue removal **(Supplementary Table S1; Extended Data Fig. 3)**.
175 For example, K fertilizer rates ranged from *nil* in the western Pampas, eastern Africa,
176 and US western Corn Belt, to 236 kg K ha^{-1} y^{-1} in southeast China, while residue
177 removal ranged from *nil* in South America to up to 92% in rice systems in Africa
178 **(Supplementary Table S2)**. Our database represents well the range in yield, K fertilizer
179 use, and soil K levels across cropping systems, without indication of a publication bias
180 **(Extended Data Figs. 3 and 4)**. For example, average yields reported in the surveys
181 used to calculate K balances were consistent with crop yields reported in official
182 statistics such as FAOSTAT (www.fao.org/faostat). On the other hand, mean crop yields
183 in field trials were, on average, 25% higher than those reported in official statistics likely
184 because crop and soil management are optimized and N and P limitations were
185 minimized in the experiments.

186

187 Our analysis of field trials showed that, with few exceptions, soil K supply alone could
188 not meet crop K requirement at current yield levels **(Fig. 1A)**. Across all systems,
189 omission of K fertilizer reduced yields by an average of 11%, confirming that indigenous
190 soil K supply alone is insufficient to sustain current production levels in major cropping

systems, with largest yield differences (i.e., lower yield without K) in South Asia, Southeast Asia, China, U.S. Cotton Belt, and rice systems in Africa. Smaller yield differences were observed in South America, the U.S. Corn Belt, and maize systems in Africa, yet large variation was observed among cropping systems within these regions. Potassium fertilizer application significantly increased net profit in 78% of the cropping systems, with an average additional profit of US$285 ha^{-1} y^{-1}, which was, in turn, 3.7-fold greater than fertilizer costs **(Fig. 1B)**. Conversely, the economic benefit of K fertilizer application was smaller and more uncertain in the Latin American Pampas, U.S. Corn Belt, and maize systems in Africa, consistent with the small yield increase due to K application observed in these cropping systems.

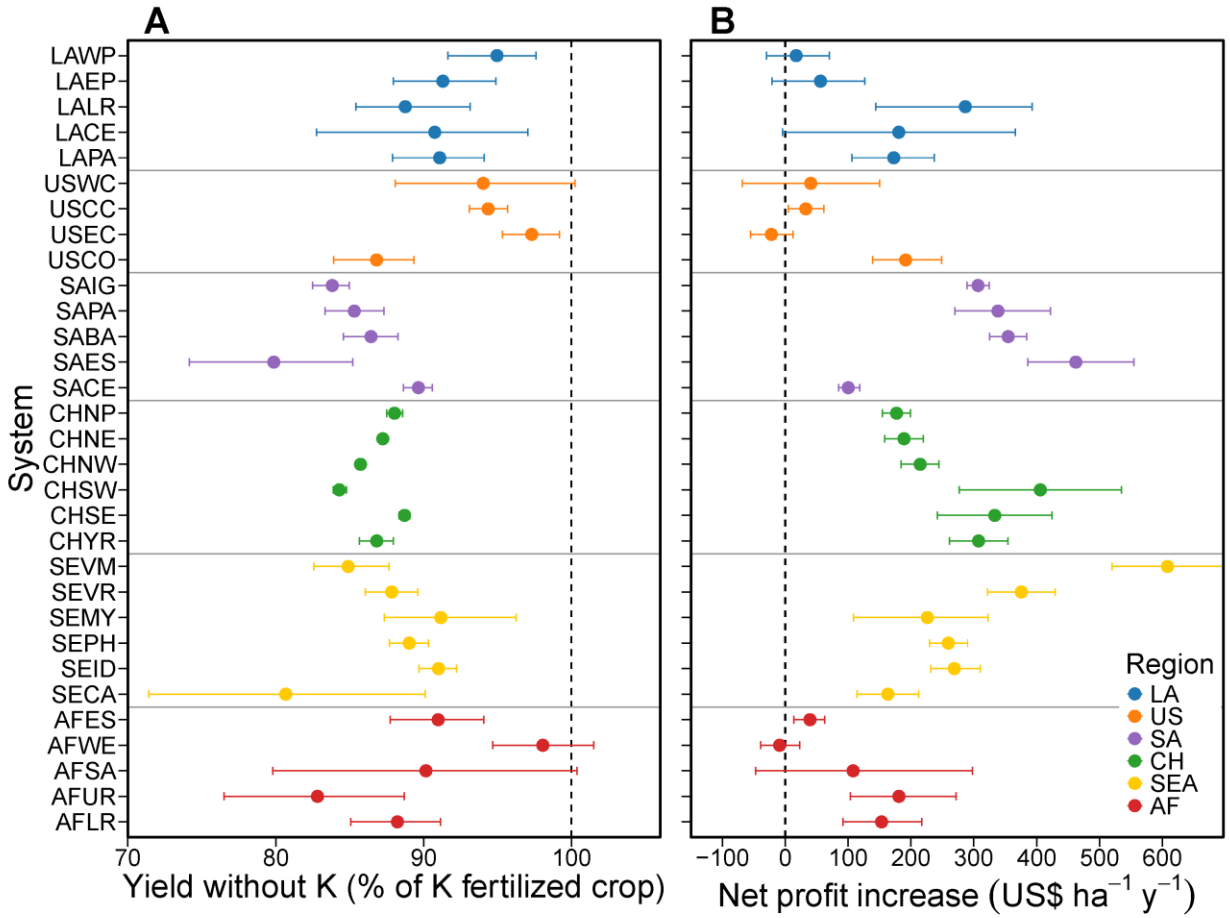


Figure 1. Crop yield without K fertilizer and additional profit due to K fertilizer application. *(A) Crop yield without K fertilizer relative to K-fertilized crops in field trials. (B) Changes in yearly net profit due to K fertilizer based on yield response to K fertilizer and average global grain and fertilizer prices. Means (circles) and 95% confidence intervals (horizontal bars) are shown. Means were weighted by crop-specific harvested area within each cropping system. Confidence intervals are not shown when they overlap with symbols. Colors and first two characters of cropping system codes refer to geographic location: Latin America (LA), United States (US), South Asia (SA), China (CH), Southeast Asia (SEA), Africa (AF). Individual cropping systems are the western (LAWP) and eastern Pampas (LAEP) and associated lowland rice area (LALR); Cerrado in Brazil (LACE); Paraguay (LAPA); the western (USWC), central (USCC), and eastern (USEC) Corn Belt and Cotton Belt (USCO) in the U.S.; the Indo-Gangetic Plain in India and Nepal (SAIG), Pakistan (SAPA), and Bangladesh (SABA); eastern (SAES) and central (SACE) regions of India; North Plains (CHNP), Northeast (CHNE), Northwest (CHNW), Southwest (CHSW), and Yangtze River Valley (CHYR) regions in China; Mekong (SEVM) and Red River Deltas (SEVR) in Vietnam; lowland rice area in Myanmar (SEMY), Philippines (SEPH), Indonesia (SEID), and Cambodia (SECA); South Africa (AFSA); and eastern (AFES) and western (AFWE) regions of Africa, and associated upland (AFUR) and lowland rice (AFLR) areas. See* ***Supplementary Tables S1-S2*** *for detailed cropping systems description. The number of observations for each system is shown in* ***Supplementary Table S3****. Data are provided as Source Data.*

Biophysical and management drivers for K limitation

We investigated the factors explaining variation in K limitation across the 31 cropping systems, including soil properties, climate, and agronomic practices **(Figure 2; Extended Data Fig. 5)**. Soil exchangeable K in the topsoil varied widely across cropping systems, with highest average levels in the temperate environments of the Latin American Pampas and western U.S. Corn Belt (>250 mg kg^{-1}) and lowest in (sub-) tropical regions of Latin America and South and Southeast Asia (<100 mg kg^{-1}), which was broadly consistent with greater weathering intensity and lower mineral K reserves in tropical soils **(Extended Data Fig. 6)**. While exchangeable soil K provides a useful starting point to diagnose K limitation, it explained only part of the variation in K limitation across cropping systems, due to the influence of clay mineralogy and agronomic management **(Figure 2)**. For example, the yield without K application, relative to the K-fertilized crop, varied from 80% to 97% in cropping systems with low average soil K concentration (<150 mg kg^{-1}). In general, K limitation was larger in cropping systems with low soil K, rich in K-fixing clay minerals (e.g., vermiculite), which tend to be more prevalent at lower latitudes, and negative long-term K balances due to a combination of high cropping intensity (*i.e.*, number of crops per year), small K input, and especially high crop residue removal.

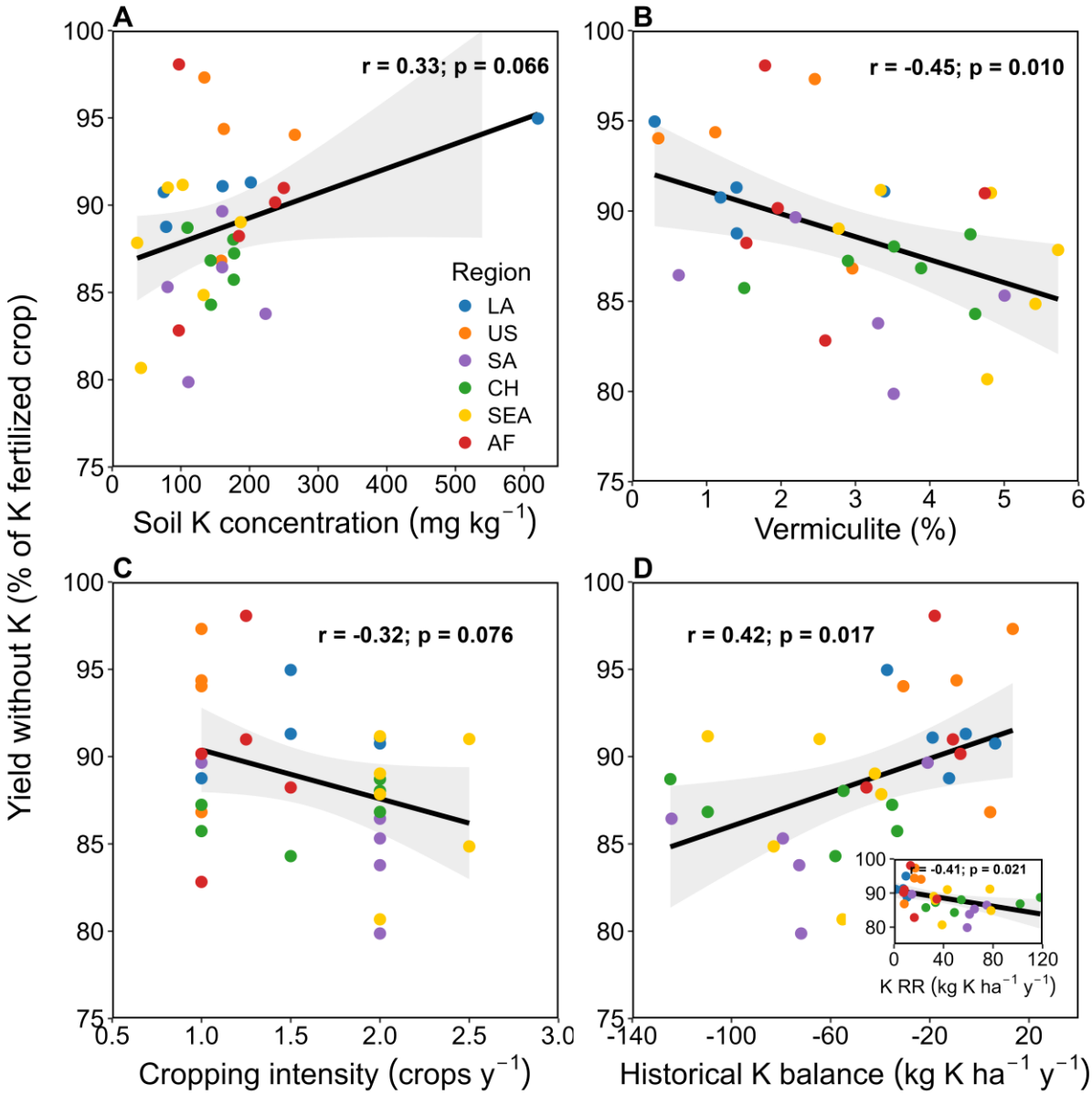


Figure 2. Relationship between crop yield without potassium (K) fertilizer and selected soil and management variables across the 31 cropping systems. *Yield is expressed as the quotient between K unfertilized and fertilized crops using data from field trials. Soil exchangeable K concentration in the topsoil is expressed as ammonium acetate equivalent (see Methods). Cropping intensity is the number of crops grown on the same piece of land during a 12-month period. See methods for calculation of the historical annual K balance. Inset in (D) shows the relationship with historical K output through residue removal (RR). Each datapoint corresponds to a weighted average of an individual cropping system. Colors show geographic location: Latin America (LA), United States (US), South Asia (SA), China (CH), Southeast Asia (SEA), and Africa (AF). The grey area shows the 95% CI of the linear regressions. Data are provided in Source Data. See* ***Supplementary Tables S1-S2*** *for detailed description of cropping systems. See* ***Extended Data Fig. 5*** *for entire analysis of biophysical and management factors.*

On-farm input-output K balances of fields

A potential yield limitation due to insufficient soil K supply can be ameliorated by applying K fertilizer. Thus, assessing the actual degree of K limitation across the 31 cropping systems requires quantification of external K inputs and K balances in farmers' fields. In our study, we calculated an annual and partial K balance at the field level for each system using a tier-based approach **(see Methods)** that prioritized on-farm data on K inputs and outputs and relied on aggregated national or regional values only when more granular data were unavailable **(Figure 3; Supplementary Table S4; Supplementary Equations S1-S9)**. A negative balance would indicate that crop K removal via harvested products and residue removal is larger than inputs from inorganic and organic fertilizers, irrigation water, and seeds, while a positive balance would suggest a K surplus. Persistent negative K balances were observed across South Asia, Southeast Asia, and Africa (–42, -23, and -32 kg K ha^{-1} y^{-1}, respectively), reflecting chronic nutrient mining driven by low K fertilize ruse, intensive cropping, and/or extensive residue removal, especially in Africa. Likewise, balances were negative in the western Pampas and U.S. Corn Belt (–44 and -33 kg K ha^{-1} y^{-1}, respectively) due to a combination of lack of K fertilizer use, due to high soil K availability, and high yields and thus large K removal through harvested grain. Conversely, K balances were positive in the Brazilian Cerrado and most cereal-based systems in China (+46 and +55 kg K ha^{-1} y^{-1}, respectively) due to high K fertilizer rates and/or greater residue retention. In some cases, the K balance varied substantially between adjacent countries. For example, K balances ranged from -29 kg K ha^{-1} y^{-1} (Bangladesh) to -55 kg K ha^{-1} y^{-1} (Pakistan) in

South Asia, or from -35 kg K ha^{-1} y^{-1} (Argentina) to +39 kg K ha^{-1} y^{-1} (Brazil) in the eastern Pampas region in Latin America.

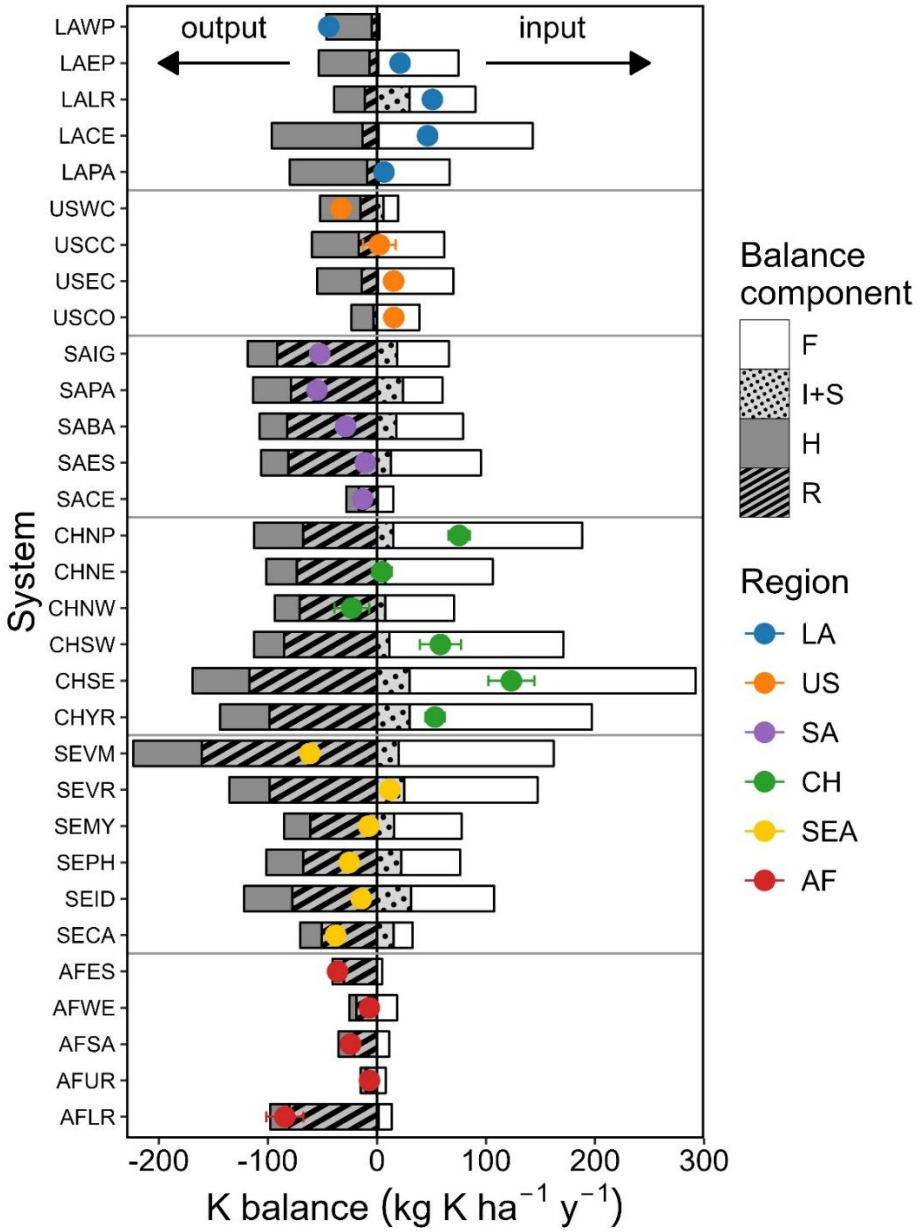


Figure 3. On-farm potassium (K) balance across 31 cropping systems. *Colored circles represent the mean K balances per year while whiskers indicate the 95% confidence intervals. Horizontal bars show individual K balance components, including inorganic and organic fertilizers (F), irrigation and seed (I+S), harvested yield (H), and residue removal and burning (R). Cropping systems are described in* ***Supplementary Table S1*** *and their codes shown in* ***Fig. 1****. Means were weighted using crop-specific harvested areas in each crop system. Number of observations for each cropping system is shown in* ***Supplementary Table S3****. Data are provided in Source Data.*

The yield without K fertilizer relative to fertilized crops serves as a proxy of soil's capacity to meet crop K requirement, whereas the on-farm K balance indicates the extent to which external K inputs (fertilizer, seed, irrigation water) are sufficient to offset the K outputs through the harvested product and crop residue**.** Plotting these two variables (i.e., yield without K relative to K-fertilized crops *versus* K balance) together allowed us to categorize cropping system regions into three groups and derive conclusions about the current degree of K limitation **(Figure 4; Extended Data Fig. 7)**. The first group includes cropping systems in South Asia, Southeast Asia, and Africa (a total of 124 million hectares), where soils exhibit limited K supply and negative K balances. The second group comprises cropping systems currently buffered by high native soil K reserves, but where continued nutrient removal without replenishment indicates an emerging K limitation, including the western Pampas and the U.S. Corn Belt. This finding is not surprising as these systems still show high inherent soil K levels, allowing high productivity at the expense of soil K depletion **(Extended Data Fig. 8)**. Maize-based systems in West Africa also have low yield without K and negative K balances, but productivity is low; and K limitation might become important as agronomic constraints to yield are overcome. Additionally, strong field-to-field variation in manure application history may be masking the actual K limitation[21,22]. The third group includes the Cerrado, most cereal-based systems in China, and rice systems in South America, where soils have limited capacity to meet crop K requirements, but large K fertilizer inputs currently alleviate any potential K limitation.

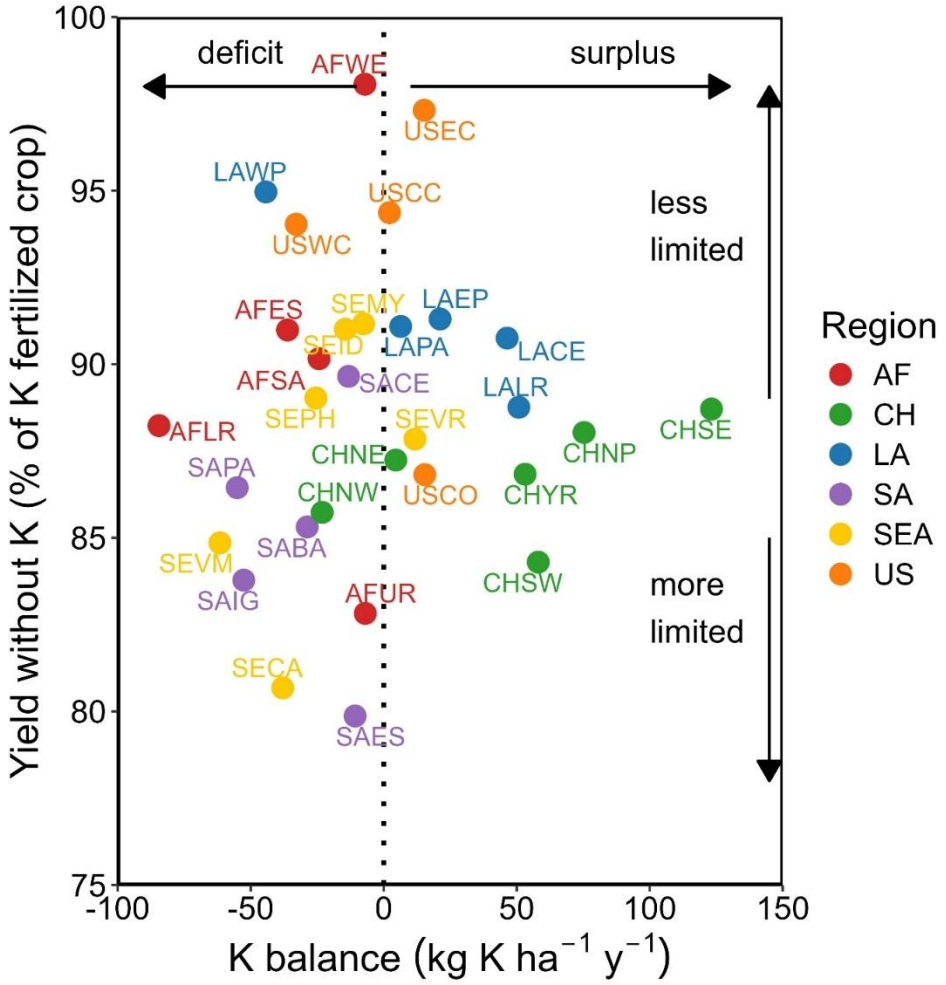


Figure 4. Categorization of 31 cropping systems based on yield without K and K balance. *Yield from crops that did not receive K fertilizer relative to K-fertilized crops in field trials. The K balance per year was estimated based on K inputs from inorganic and organic fertilizers, seed, and irrigation water, and K outputs from harvested grain and residue removal and burning. Note that by plotting these two variables, we aimed to categorize crop systems in relation to soil capacity to supply sufficient K and current K balance, without implying a cause-effect relationship between variables. Cropping system codes are shown in the caption to* ***Fig. 1****. Data are provided in Source Data. Means were weighted using crop-specific harvested areas within each cropping system. Location of the cropping systems and categories are shown in* ***Extended Data Fig 6****.*

Negative K balances over extended periods can lead to declining soil K availability and crop yields. We initially estimated that avoiding negative K balances across the 31 cropping systems would increase the K fertilizer requirement by 30% relative to the current baseline, from about 15.0 ± 0.2 to 19.3 ± 0.3 million metric tons (mean ± 95%

CI) **(Figure 5)**. However, achieving a neutral K balance for current yields should not be the goal in regions where a large 'yield gap' exists between average farmer yields and the attainable yield with good agronomic management[23]. In those cases, larger K inputs will be required to achieve higher yields, along with optimization of other nutrients and agronomic practices. In our study, we defined the attainable yield as 80% of the yield potential estimated for each cropping system based on local weather and soil conditions and accounting for water limitation **(see Methods)**. For each system, the K input requirement to reach zero-K balances with the attainable yield (i.e., yield intensification) was estimated following a K-replacement approach. The latter assumes that K inputs via organic fertilizer and irrigation and K outputs via crop residue management will not change. Achieving attainable yields while avoiding further soil K depletion would require annual K inputs to increase by ca. 68%, equivalent to an additional 9.7 ± 0.4 metric tons (mean ± 95% CI), across the 31 cropping systems. Largest increases in K input, relative to current use, will be needed in regions where current yield gaps are large and K fertilizer use is low, as is the case in Africa and South Asia (+103 and +100 kg K ha^{-1} y^{-1}). Likewise, substantial increases will be required in rice systems in Southeast Asia (+81 kg K ha^{-1} y^{-1}) due to a combination of high cropping intensity, intermediate yield gaps, and low K fertilizer rates. The K input will also need to increase, eventually, in regions where current K fertilizer use is low because of high, yet declining, soil K levels (e.g., western Pampas and western U.S. Corn Belt) **(Extended Data Figure 8)**. Conversely, current K inputs in the Brazilian Cerrado, and most cropping systems in China and the U.S., appear sufficient to support attainable yields and sustain soil health, although continued monitoring remains essential.

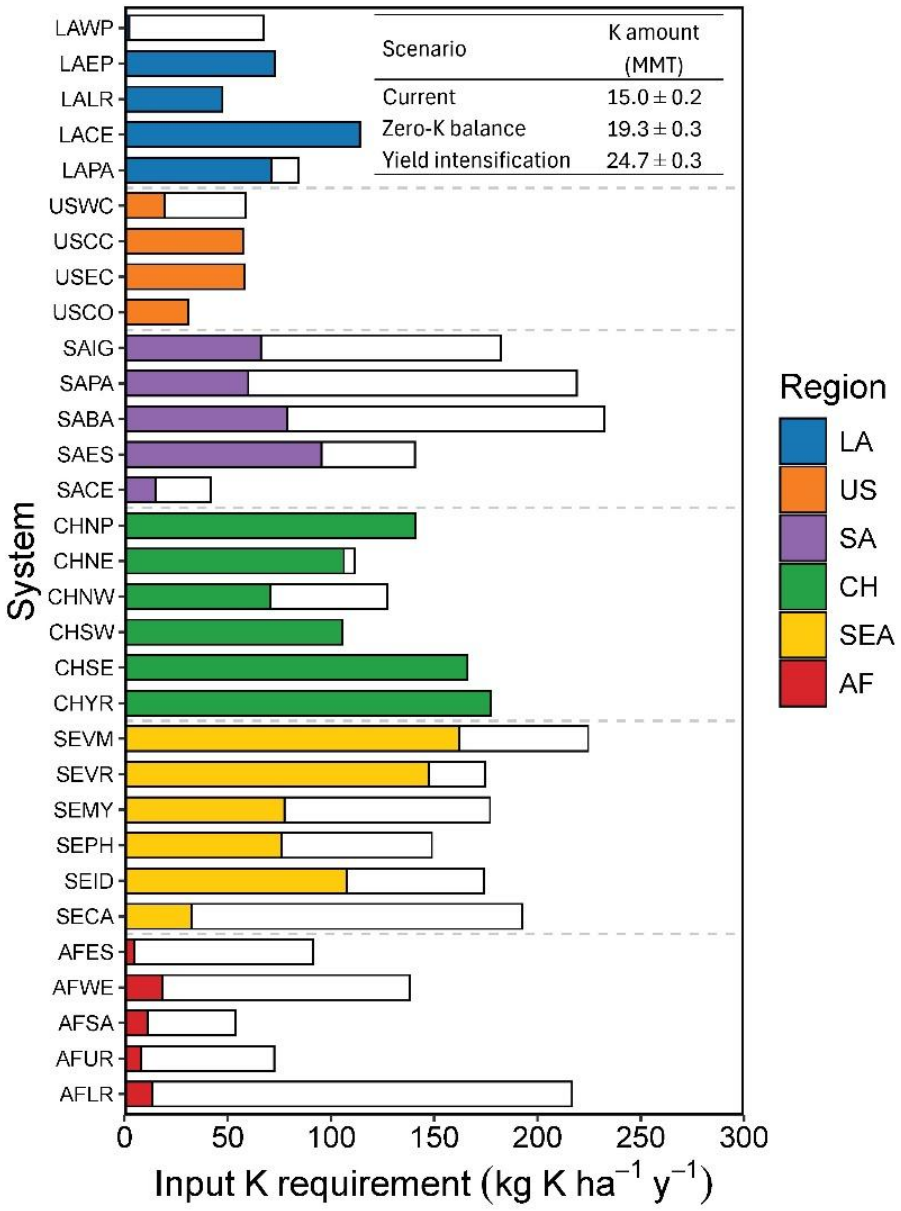


Figure 5. Potassium (K) input requirement per year to achieve yield intensification and avoid negative K balances. *Estimated total K input requirement to support the locally attainable yield as determined by weather and soils (full bar length). Also shown are the current K input and the extra K input requirement for yield intensification (solid and empty portions of bars, respectively). Attainable yield was estimated as 80% of the yield potential, which is a reasonable yield target for farmers with access to inputs, markets, and extension services (see Methods). Inset shows current inorganic K fertilizer use (mean ± CI) across the 31 cropping systems and the K requirement estimated for two scenarios: zero-K balance and yield intensification. See* ***Methods*** *for estimation of uncertainty and* ***Extended Data Fig. 9*** *for sensitivity analysis. Cropping system codes are shown in* ***Fig. 1****. Cropping systems are described in* ***Supplementary Table S1****. Weighted means were calculated based on crop-specific harvested areas within each cropping system. Data are provided as Source Data.*

Discussion

Meeting future demand for food, feed, fiber, and biofuel without massive cropland expansion will be a major challenge [27]. Achieving this goal will require an explicit effort to increase land productivity so that farmers reach attainable yield as determined by local weather and soils [27,28]. Through a combination of analysis of legacy K data from the past 25 years, meta-analysis, and crop modeling, our study showed that soil K supply is often insufficient to meet crop requirements over extended cropping periods and at high yield levels **(Figure 1)**. In many systems, current K inputs fail to offset crop K removal, resulting in progressive soil nutrient depletion and increasing dependance on declining native soil K reserves **(Figures 3 and 4, Extended Data Fig. 7)**. We also found K fertilizer application to be profitable across regions in most cases, except when soil K is high (e.g., western Pampas and U.S. Corn Belt)[24–26] or when fields can strongly vary in K status due to spatial variation in manure application and yield is low due to inefficient agronomic management (e.g., maize-based systems in Africa) [21,22]. Across the 31 cropping systems, we estimated that K fertilizer requirement will need to increase by 30% to avoid current negative K balances and by 68% to achieve yields of about 80% of the local yield potential. Fortunately, large exploitable K resources exist, and more mining capacity is under development already, yet they are unevenly distributed, implying that ensuring global crop K nutrition will require trade without barriers or disruptions and improved K recycling at local level. We conclude that sustaining soil health as well as reaching yield intensification will require a substantial increase in K fertilizer use to boost soil fertility, especially in the Global South, along with improved K

management in agroecosystems, including on-farm crop residue use and manure management to improve K recycling, and other K sources that may contribute to K input (e.g., organic resources, irrigation water).

Our study allowed identification of regions where current K inputs need to increase either now or in the future to sustain higher yields, providing vital input to guide policies, investments, and R&D programs **(Figures 4 and 5; Extended Data Fig. 7)**. For example, cropping systems in which K inputs need to increase to sustain higher yields include those in South Asia, Southeast Asia, and Africa. In those cases, greater K fertilizer use, improved residue management, and improved recycling of organic components that remain after processing are needed to overcome the current K limitation and prevent further soil K mining. Several systems that were historically not limited by K, including the US western Corn Belt and Pampas, appear to be transitioning to a K limitation due to long-term nutrient mining. Indeed, our study shows rapid declines in soil K levels and emerging evidence of yield responses to K fertilizer addition in these cropping systems **(Figure 1; Extended Data Fig. 8)**, which is consistent with other local studies [24–26,29]**.** In these cases, a sound approach is to closely monitor soil K and yield responses over time and adjust fertilizer input as needed. Finally, there are cropping systems showing a large K surplus, where room exists to optimize K rates and/or yield to improve cost-effectiveness, as is the case in China and Brazil.

These findings also highlight the need to improve diagnostic approaches for K management in farmer fields. At present, agricultural practitioners rely on estimated soil exchangeable K (e.g., Mehlich-1, Mehlich-3, or ammonium acetate soil test methods) to inform K fertilizer requirements for optimal crop production. In our study, we found that half of the 31 cropping systems exhibited average soil K below 150 mg kg^{-1} **(Extended Data Figure 6).** Exceeding this soil K level is regarded in the literature as sufficient to avoid plant deficiencies in many cropping systems [30,31]. However, we found that soil K was a poor predictor of variation in soil K supply across cropping systems, even in those with low soil K, due to differences in clay mineralogy and history of agriculture **(Figure 2).** This finding is consistent with previous studies reporting lack or weak relationships between soil K and crop K uptake or yield response to K application [32–34]. Although our study makes advances on current understanding of the drivers of K limitation, more research and better plant-soil models are needed to quantify crop K availability from both soil and fertilizer in a range of conditions to predict when a cropping system can become K-limited and inform associated agronomic management to overcome this limitation. In the meantime, generic approaches that combine data on soil K, crop removal for a given yield target, and local agronomic context (*e.g.*, residue management, other K sources such as manure and irrigation water), complemented with field strips to identify cost-effective rates, should continue to inform K management across environments.

Promoting higher K use and improved management in agro-ecosystems will also require sound policy. For example, variation in K balances across cropping systems and

countries reflects differences not only in fertilizer use, but also differences in subsidy structures, fertilizer type, and residue use policies. Recent studies from Southeast Asia and South Asia have shown that fertilizer subsidies tend to favor N- and P-containing fertilizers over K, leading to widespread low K fertilizer use and nutrient imbalances[35–38]. Likewise, many governments are promoting greater use of crop residue for other uses such as animal feed, mushroom production, and biofuel due to public concerns associated with residue burning and CH_4 emissions in rice systems[39–41]. Most of the K absorbed by crops during the growing season remains in the vegetative organs at maturity[11]. Thus, the K input that is needed to offset the K export through residue removal is proportionally larger than that required to compensate for K removal via the harvested organs. Our sensitivity analysis shows that K fertilizer requirement is extremely sensitive to residue management **(Extended Data Fig. 9)**. Thus, K fertilizer requirement could increase under a scenario of greater crop residue use. For example, the K requirement associated with the attainable yield would increase from 24 to 33 million tons if crop residue removal increases from 41% at present to 75% in the future. Policies promoting residue removal for feed, fuel, or industrial uses must explicitly account for associated K export and replacement costs to avoid accelerating soil nutrient depletion subsidy programs could help sustain long-term soil fertility and crop productivity.

The approach followed in our study, based on yield responses, nutrient balances, and crop modeling, serves as a “blueprint” for future studies assessing nutrient management at the global level, ensuring agronomic rigor and local relevance. However, important

limitations remain. First, our study did not include important crops such as oil palm, forages, and sugarcane and other key crop-producing regions (e.g., Europe and Australia). We note that our 31 cropping systems account for a large fraction of global crop production and the lack of data for other crops constrained our capacity to include others in our study. Europe was not included because it has a long history of K and manure use in agriculture, making it less likely that K limitations are widespread. We recognize, however, that this may not be the case in Eastern Europe or countries of the former Soviet Union. We excluded oil palm – a major consumer of potash fertilizers – because the role of K management in that crop is widely known[42,43] and deficits are well documented for smallholder systems[44]. Deficits are also documented for other crops with large K removal, such as bananas, cassava, and yams in smallholder systems in East Africa[33,45], sugarcane[46,47], and forage crops[48,49], but available information is scarce. Second, there may be mismatches among soil, yield, and K-balance databases and inherent biases. For example, crop nutrient trials may be biased towards sites where a yield response to fertilizer is expected and/or located at sites with favorable soils and weather and thus higher yield levels. To the best of our efforts, we collected data that were representative of the yield, soils, and management of target cropping systems. Indeed, comparison of our average yields, K fertilizer rates, and soil K levels against independent sources shows reasonable agreement and no clear bias **(Extended Data Fig. 3)**. Likewise, meta-analyses may be affected by publication bias; however, our data collection approach, which included unpublished datasets, helped mitigate this issue **(Extended Data Fig. 4).**

Our study is also subjected to uncertainty in underlying data sources and assumptions to estimate on-farm K balances and assess K fertilizer scenarios. For example, in the absence of measured data, we assumed fixed grain and straw K concentrations and harvest index by crop to estimate crop K removal. Although recent studies have shown large variation in these parameters[11], their impact on the estimation of K removal in harvested product is relatively small compared with yield variation. Likewise, there is also uncertainty associated with K removal through crop residue and K inputs via irrigation. To estimate these fluxes, we followed a tiered approach, prioritizing measured data and relying on national or regional averages only when local data were unavailable **(Supplementary Table S4)**. We quantified the uncertainty of our scenario assessment due to variation in the underlying data and the sensitivity to nutrient-balance parameters, and we found that the results can be considered robust **(Figure 5; Extended Data Fig. 9)**. Finally, our K balance is incomplete as we did not account for K losses through leaching, runoff, and/or erosion due to lack of measured data to estimate these fluxes for the target cropping systems. Inclusion of these losses would make K balances more negative in most systems, reinforcing our conclusions regarding the current K limitation. Likewise, the amount of K fertilizer needed to avoid soil K depletion and avoid K limitation may be larger than the crop K removal, for example, in soils with high K fixation or those where soil K needs to be built, which would make our estimates of K fertilizer requirements conservative. Overall, although these uncertainties and limitations may affect the magnitude of estimated K balances and K input requirements, they are unlikely to alter the main conclusion that K limitation is widespread and increasing in importance across major cropping systems.

Methods

Cropping system selection. We followed two steps to select the cropping systems for our study. First, we identified the most important crop-producing regions within each continent and, within each of them, the most important cropping systems. Here, a "cropping system" refers to a given combination of crops grown sequentially in a specific region under similar biophysical conditions and management **(Extended Data Figs. 1-2; Supplementary Table S1)**. Following this approach, we selected cereal-legume and rice systems in South America, maize-soybean and cotton systems in North America, and cereal-based systems in Africa, the Indo-Gangetic Plain, and Southeast and East Asia. We did not consider cropping systems in western Europe given the lack of evidence on K limitation [50–52]. Likewise, we did not include Oceania given the small share of global cropland. Other systems were not included given the lack of available data on yield responses to K fertilization (e.g., perennial and vegetable crops, cotton in China). On the other hand, we further sub-divided cropping systems when there were strong differences in yield levels, K fertilizer management, and/or crop residue removal across countries or regions within countries. For example, the US Corn Belt was subdivided into western, central, and eastern regions and the Indo-Gangetic Plain into eastern (Bangladesh), central (India and Nepal), and western (Pakistan) regions. Following this approach, we selected a total of 31 cropping systems, across 42 countries that collectively account for 60%, 73%, and 57% of global cereal, oilseed, and fiber production, respectively.

Sources of data. Our goal was to assess the current degree of K limitation using soil, plant, and management variables. Thus, we compiled data collected from field-grown crops after 2000. We collected three types of data: (i) topsoil (from 0-0.15 m to 0-0.30 m) exchangeable K concentration (*n* = 22 million samples), (ii) yield from experiments that included treatments with and without K application, both receiving N and P fertilizers to avoid limitations from these nutrients (*n* = 66,300 trials), and (iii) the variables needed to estimate on-farm K balances (*n* = 117,000 fields, Supplementary Table S3). Data were retrieved from published scientific manuscripts, open data repositories, dissertations, extension bulletins, project reports, conference presentations, and direct requests to researchers in public and private sectors, including universities, research organizations, soil testing laboratories, and seed and fertilizer industries. This diversity of sources helped reduce the publication bias.

To the extent possible, we ensured that our soil K data came from samples collected in croplands that coincide with the geographic extent of our target cropping systems. Specifically, we excluded soil samples located in pixels with less than 10 ha of harvested area for the crops included in each cropping system, based on SPAM[53,54]. In our study, soil K concentration is expressed as ammonium acetate-extractable K (K-AA) equivalent. If soil K concentration was determined through a different extraction method (e.g., Mehlich-1 or Mehlich-3), we adjusted the values to K-AA equivalents using conversion factors from the literature **(Supplementary Figure S1)**. On the other hand, we did not attempt to adjust soil K concentration based on sampling depth, which ranged from 0.15 to 0.30 m across observations.

For field experiments, we attempted to collect data from individual replicates and, when this was not possible, we recorded average treatment values together with a measure of experimental error and/or the number of replicates per trial. We considered only short-term trials (up to two consecutive crops) that included treatments with and without K (usually applied as potassium chloride), both receiving N and P fertilizers to avoid limitations from these nutrients. All experiments included a K-omission treatment and at least one treatment receiving K fertilizer. When more than one K rate was evaluated, we selected the rate that produced the largest average yield response relative to the K-omission treatment. Likewise, if different application timings or placement methods were evaluated, treatments were averaged within each K rate, and we selected the one showing the largest response. We did not attempt to disentangle the potential contribution of chloride to the observed yield responses. However, potassium chloride is the most widely used K fertilizer globally, and yield responses across trials were generally consistent with indicators of soil K availability and plant K nutritional status [55–57], suggesting that the observed responses predominantly reflect K limitation rather than chloride effects. Finally, data needed to estimate on-farm K balances were retrieved from diverse sources, including survey data, official statistics on yields and K fertilizer use, literature review, and expert opinion (**Supplementary Table S4**). These data included yield, K fertilizer rate, irrigation water applied and associated K concentration, seeding rates and associated K concentration, crop residue management, including removal and burning, and manure amount, type, and associated K concentration. In all

cases, K is reported on an elemental basis while yields are reported at standard moisture content for commercialization for each crop.

Estimation of relative yields without K fertilizer and economic return to K fertilizer. Absolute yield and yield responses to K fertilization vary across cropping systems due to differences in crop species, water regimes, and climate and soil properties. To account for these differences, we determined the K limitation by calculating yield without K fertilizer relative to K-fertilized crops for each field trial as follows:

$$RY = \frac{Y_0}{Y_K} * 100 \quad \text{(Eq. 1)}$$

where Y_0 and Y_K are the yields without and with K fertilizer addition, respectively, in crops that received high and equal amounts of N and P fertilizer. We quantified the economic return to K fertilizer addition as follows:

$$Net\ profit\ increase = (Y_K - Y_0) * G\$ - FKA * FK\$ \quad \text{(Eq. 2)}$$

where G$ and FK$ are the price of the harvested product (US$ Mg^{-1}) and K fertilizer (US$ kg^{-1} of K), respectively, and FKA is the applied K fertilizer (kg K ha^{-1}). Prices were

586 based on global prices for crops and muriate of potash over the past 20 years[58,59]. For
587 cotton, seed yield responses were converted to lint yield using a lint fraction of 38%
588 while an average milling rate of 67% was assumed for rice [60,61]. The cost of fertilizer
589 application was not included in our economic return due to varying costs across regions
590 and insufficient data. Likewise, we did not account for local market prices, national
591 subsidies on fertilizer or other factors affecting farm gate prices of inputs or crop
592 products.

593

594 **Estimation of on-farm K balance.** On-farm input-output K balances were estimated
595 according to Murrell et al.[10] as follows:

596

597 K balance = KFE + KOS + KIR + KSE – KHP – KRR - KRB (Eq. 3)

598

599 which include K inputs from synthetic fertilizer (KFE), organic sources (KOS), irrigation
600 water (KIR), and planted seed (KSE), and K outputs through harvested product (KHP)
601 and residue removal and burning (KRR and KRB, respectively), all expressed in
602 elemental K (kg K ha^{-1} $crop^{-1}$) **(Supplementary Equations S1-S9)**. Mean K losses
603 through ash generated during crop residue burning were estimated at 26% based on
604 average values reported in the literature **(Supplementary Equation S8).** Annual K
605 balances were estimated at the cropping system level by considering their average crop
606 intensity (**see Data Analysis**). Due to insufficient experimental data and a lack of
607 generic predictive models, we excluded K inputs through atmospheric K deposition and

608 K outputs through leaching, runoff, and erosion. Given the different data sources
609 (surveys, literature review, official statistics) and spatial aggregation (field, sub-national,
610 and national levels), we used a tiered approach to determine the best sources of data
611 for estimating the K balance for each country **(Supplementary Table S4)**. Following this
612 approach, we prioritized field-level data (tier 1) and turned to other sources of
613 aggregated data, such as national statistics or regional averages (tier 2) or global
614 averages (tier 3), when more granular field-level data were unavailable
615 **(Supplementary Table S4)**. For each field-level K balance calculation, the minimum
616 requirement was the availability of crop yield and K inputs from synthetic fertilizer at the
617 tier 1 level. To calculate some components of the K balances, we had to rely on average
618 global values. For example, to estimate crop K removal, we used crop-specific average
619 values of harvest index and K concentration in the harvested product and crop residue
620 reported in the literature **(Supplementary Tables S4-S5)**. Likewise, average K
621 concentrations in compost and manure reported in the literature were used to estimate
622 K inputs from organic sources. The same approach was used to determine the fraction
623 of K lost through ashes when crop residue is burned **(Supplementary Equations S1-**
624 **S9)**.

625

626 **Data analysis.** A data quality-control procedure was applied to remove outliers and
627 potentially erroneous observations. For example, we removed values below the 1st
628 percentile and above the 99th percentile of the soil K distribution in each cropping
629 system. Likewise, we removed field trials with Y_K substantially below national average in
630 the same years (based on FAOSTAT, www.fao.org/faostat), suggesting that other factors

may have limited the crop yield response to K fertilizer addition. To assess potential biases, we compared the mean soil exchangeable K from the trials with that estimated from independent sources such as field values coming from soil testing labs **(Extended Data Fig. 3)**. Likewise, we compared the average yield from the experiments and yields and K fertilizer rates from the on-farm balances against national data reported in FAOSTAT (www.fao.org/faostat) and IFASTAT (www.fertilizer.org/market-intelligence/ifastat/), respectively. Some of these comparisons were inherently biased due to mismatches between the target cropping system (typically subregions within a country) and the national data from FAOSTAT and IFASTAT, especially for large countries such as China and Brazil. Also, and not surprisingly, yields in fertilizer trials were higher than national yields due to higher NPK fertilizer rates.

To assess the overall effect of K fertilizer application on yield for each cropping system, we conducted a meta-analysis based on the logarithm of the relative yield without K fertilizer (LNRR = $\ln(Y_0/Y_K)$). Likewise, we assessed the economic benefit of K fertilizer with a meta-analysis based on net profit increase (NPI, Eq. 2). Because only a limited number of experiments reported measures of yield variability across replications (e.g., SE, standard deviation, or coefficient of variation), observations were weighted (w) by the number of replications (r), as $w_i = r_i/2$, following Adams et al. and other studies [62–64]. Observations without replication information were weighted as r = 1 (minimum weight). In cropping systems that included multiple crop species, water regimes, and/or countries, observations were also weighted by the crop-country-water-regime specific harvested area from SPAM[53,54] (**Extended Data Fig. 1)**. The final weight, hence,

combined the replication-based weight with the harvested area weight for the corresponding crop-country-water-regime combination within each cropping system, normalized to sum to one. Finally, the weighted mean LNRR and NPI, and their CI95% were obtained through percentile bootstrapping (R = 999). NPI was annualized by considering the cropping intensity of each system. Potassium limitations and economic benefits were considered significant if the LNRR and NPI bootstrap CI95% did not overlap with 0. LNRR results were back-transformed to percentage of yield reduction relative to the K-fertilized treatment for better interpretation.

To validate our approach, we compared our LNRR results to those obtained using a restricted maximum likelihood (REML) meta-analysis with weighted estimates derived from sampling variances in 13 crop-system combinations with at least 10 experiments containing indicators of the yield variance **(Extended Data Fig. 4)**. Both methods produced comparable results, with overlapping CI95%. Funnel plots were also evaluated to assess potential publication bias **(Extended Data Fig. 4)**. All meta-analyses were performed in R (version 4.4.2) using the *metafor* and *boot* packages. For other variables not subject to hypothesis testing (i.e., soil exchangeable K and K balance), CI95% of individual cropping systems were calculated as their standard error (SE) multiplied by 1.96, where SE is the square root of the sample variance divided by the number of observations. Cropping system mean K balance and variance were first calculated per crop harvest by summing up the means and variances of the K balance estimated for the individual crops in the cropping system, weighting observations by the crop-country-water-regime specific harvested area based on SPAM[53,54]. Then, K

balances mean and variances were converted to an annual basis by multiplying them by their crop intensity, as reported in **Extended Data Fig. 2.**

To assess the factors explaining variation in K limitation across cropping systems, we first examined the relationships between yield without K relative to K-fertilized crops (Eq. 1) and a set of soil, climate, and management variables **(Supplementary Table S6)**. Crop-country-water-regime specific harvested area were obtained from SPAM[53,54] and all variables were quantified for the corresponding harvested area. Soil-related variables included mean soil exchangeable K, sand and clay contents, and clay mineral composition (smectite, illite, and vermiculite). Climate variables included the annual aridity index and latitude, while management variables included historical K balance, K inputs via fertilizer, K outputs via residue removal, cropping intensity, and cropping length. Mean soil exchangeable K values were obtained directly from the compiled dataset. Sand and clay contents were obtained from SoilGrids[65], and clay mineral composition data were obtained from Ito and Wagai[66]. The aridity index for each cropping system was calculated from WorldClim[67] as the ratio of annual precipitation to potential crop evapotranspiration. All soil and climate variables were retrieved for each field trial observation based on their reported geolocation. The current K limitation on crop yields is highly influenced by prior K management in the production system. Thus, we estimated K balances (Eq. 3) and their individual components over a period of 50 years (1961-2011) using data from Ludemann et al.[50]. The length of cropping was estimated as the time since each cropping system reached 50% of current crop area using data from [68]. Pairwise correlations between yield without K relative to a K-fertilized

crop and the explanatory variables were calculated using Pearson's correlation coefficients. Based on these results, simple linear regression models were fitted for the variables that showed stronger explanatory power. Correlation analyses were performed using the *corr* package, while linear regression models were fitted using the *lm* function in R (R version 4.2.2).

Scenario assessment. Current K fertilizer use across the 31 cropping systems was calculated based on their weighted-average fertilizer rates and harvested areas. We assessed K fertilizer requirements under different scenarios of K balance and crop yields. First, we investigated a scenario ("zero-K balance") in which current negative K balances are avoided by increasing the K fertilizer rate to a level that ensures a neutral K balance across all cropping systems. We are aware that increasing K fertilizer rates may not be necessary in cropping systems where soil K levels remain high (e.g., the western Pampas and the U.S. Corn Belt). However, these systems will need to increase K fertilizer use sooner or later as yields continue to rise and soil K levels keep dropping as documented in recent studies[24–26]. On the other hand, many systems achieve average yields that are substantially below those obtainable with good agronomic practices. Moreover, given the increasing demand for food, feed, fuel, and fiber, it would be desirable to increase yields within existing cropland to avoid massive cropland expansion and the negative impacts associated with the conversion of natural ecosystems for crop cultivation[69]. Thus, we assessed the K requirement needed to close the current "yield gap" in farmer fields ("yield intensification"). To do so, we estimated the crop K removal associated with the "attainable yield." Following the

literature, we defined 80% of yield potential as the “attainable yield” for farmers with reasonable access to inputs, markets, and extension services[23]. Such a yield level is considered a reasonable target for farmers seeking to maximize economic returns while minimizing their environmental footprint per unit of production. The yield potential is defined as the yield of an adapted crop cultivar when grown without water and nutrient limitations and kept free of weeds, diseases, and insect pests [23]. Thus, yield potential is determined by local solar radiation, temperature, carbon dioxide level, and genetic traits related to crop growth and development. In rainfed crops, yield potential is also determined by precipitation and soil properties influencing the water balance[23].

To estimate the crop K input requirements for each scenario, we assumed a replacement approach, in which farmers apply as much K fertilizer as needed to offset crop K removal through harvested product and residue removal and/or burning, after accounting for other sources of K inputs (irrigation, seed, and organic fertilizer). To estimate the amount of K removal through harvested product and residue removal and/or burning, we used average K concentration for harvested product and crop residue, harvest index, and fraction of K losses through burning as indicated for the K balance **(Supplementary Tables S4-S5; Supplementary Equations S1-S9)**. For the calculation of the attainable yield, we retrieved yield potential for each crop and water regime in each cropping system from the Yield Potential and Yield Gap Atlas (www.yieldgap.com). Unfortunately, yield potential was not available for cotton in the U.S. and South Asia, soybean in South Asia, and all crops in Pakistan. For those cases, we retrieved the best available estimates of yield potential from the literature[70–73]. The

attainable yield for each crop in each cropping system is shown in **Supplementary Table S1**. Finally, we calculated the additional K fertilizer requirement for the yield intensification scenarios for each individual crop within each cropping system as the difference between the estimated crop K input requirement to achieve the attainable yield and the current applied K fertilizer, with the latter derived from the current study. Our scenario assessment assumed no changes in crop residue management.

Uncertainty in current K fertilizer use and that under the two scenarios (*i.e.*, zero-K balance and yield intensification) was quantified through propagation of the uncertainty estimated for each crop in the cropping system as follows:

$$SE = \sqrt{\left(\sum {\sigma_{x_i}^2}/{n_i} \times Area_i^2\right)} \qquad \text{(Eq. 4)}$$

where *i* is the cropping system, σ_x^2 is the sample variance of current K fertilizer use or requirement for the given scenario across fields, *n* is the number of field observations, and Area is the harvested area of the cropping system. Four cropping systems were excluded from this calculation given the lack of field-level observations **(Supplementary Table S3)**. Attainable yields vary temporally within cropping systems, which propagate to variance in fertilizer requirements. To account for this uncertainty, we added a random error to the attainable yield, which was derived from the temporal coefficient variation of attainable yield reported in the Yield Potential and Yield Gap Atlas (www.yieldgap.com). We also evaluated the sensitivity of estimated K requirements under each scenario to uncertainty in the four components of the K balance: (i) inorganic and organic fertilizer

767 inputs, (ii) inputs via irrigation and seed, (iii) removal in harvested products, and (iv)
768 removal through residue removal and burning. Fertilizer use changes were evaluated
769 within a range of ±10% deviation in each component (relative to average values
770 estimated from our database), keeping the other three components constant. In all
771 cases, values were recalculated for the 31 cropping systems individually. Subsequently,
772 we estimated the overall fertilizer use for each scenario based on their fertilizer use and
773 harvested area and estimated the relative change to the baseline derived from our
774 analysis **(Extended Data Fig. 9)**.

775

776 **Data availability**

777 Data on yield potential from Yield Potential and Yield Gap Atlas are available at
778 https://www.yieldgap.org. Data on grain prices from the World Bank are available at
779 https://databank.worldbank.org and data on potassium chloride fertilizer costs are
780 available at https://indexmundi.com. Data on crop harvested area and yield within each
781 country from FAOSTAT are available at https://www.fao.org/faostat. Data on K fertilizer
782 use for each country and crop from IFASTAT are available at https://www.fertilizer.org/.
783 State-level data on crop harvested area, yield, and K fertilizer use for U.S. from USDA-
784 ERS are available at https://www.ers.usda.gov/. Data on the distribution of crop
785 harvested area from SPAM are available at https://www.mapspam.info. Data on residue
786 removal and burning are available at
787 https://datadryad.org/dataset/doi:10.5061/dryad.mgqnk99d1. Source data files are

provided with this paper. Data used for this study will be made available in a public repository (Dryad or Zenodo) at time of publication.

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Author contributions

W.D.C, F.A.M., A.D. and P.G. conceived the research. W.D.C., Y.L.L. and P.G. performed data acquisition and data processing, W.D.C, P.G., and F.A.M. performed the data analysis. W.D.C, F.A.M., A.D. and P.G. wrote the original draft of the paper. All

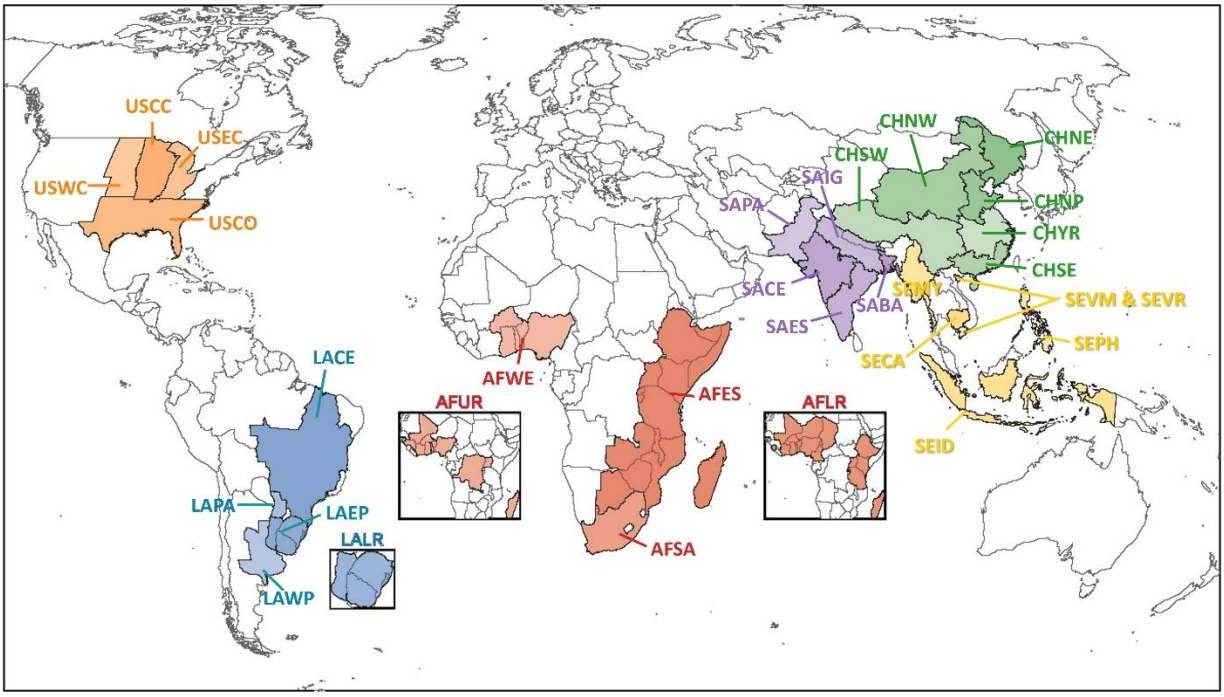
996 authors contributed to field data collection, interpretation of results, and reviewed and
997 approved the final version of the paper.

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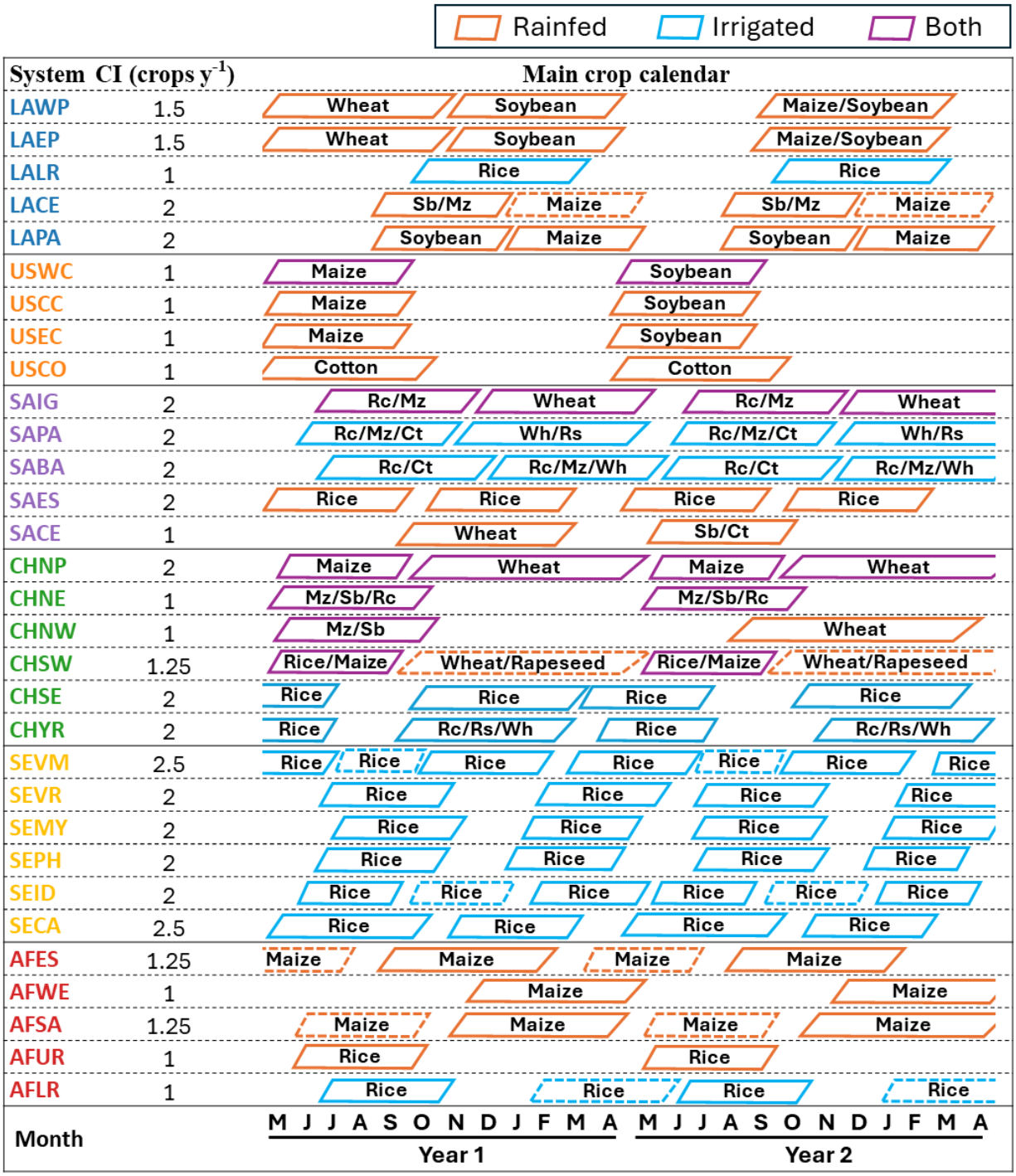
999 **Competing interests**

1000 The authors declare no competing interests.

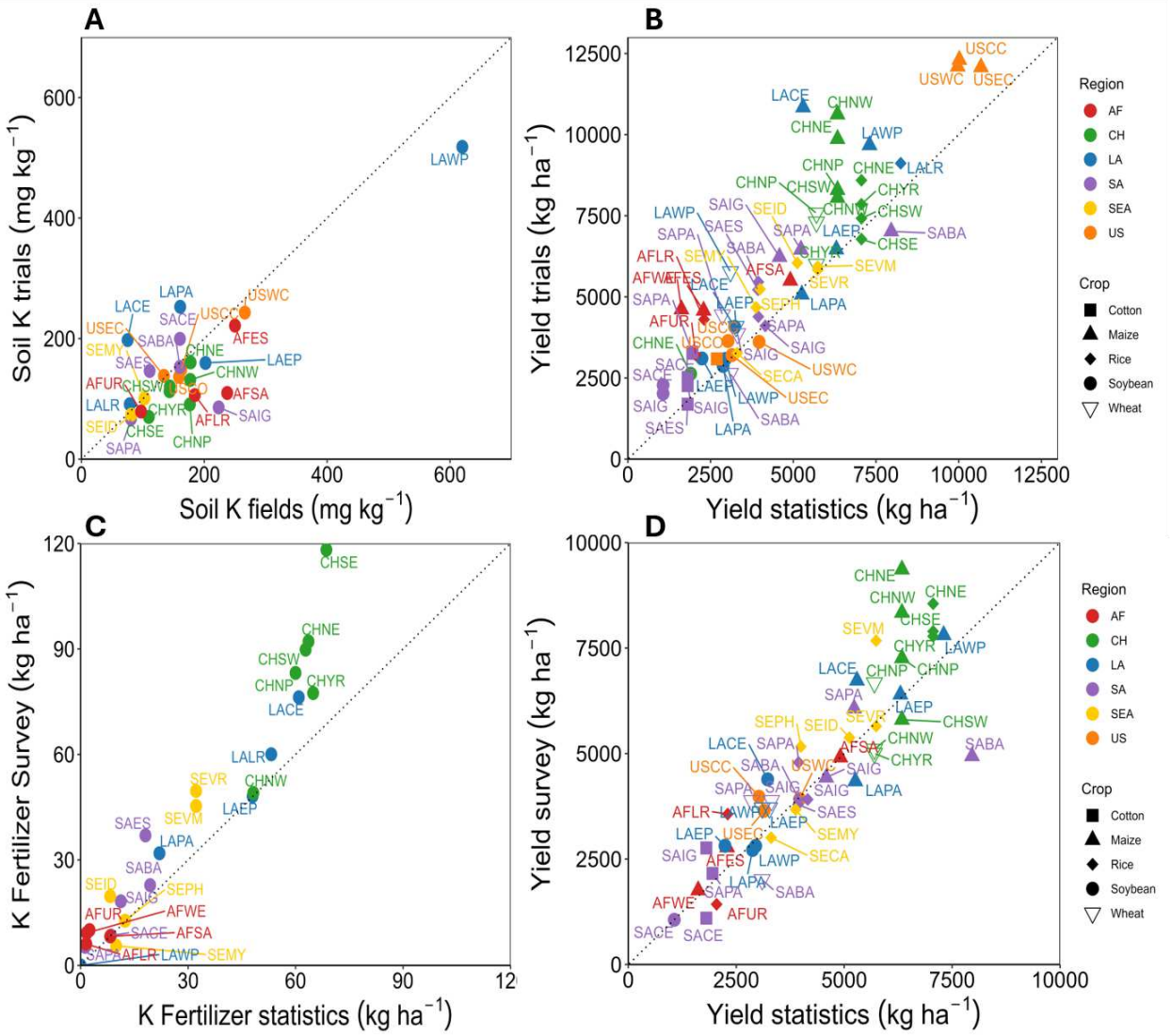
Extended Data Figures



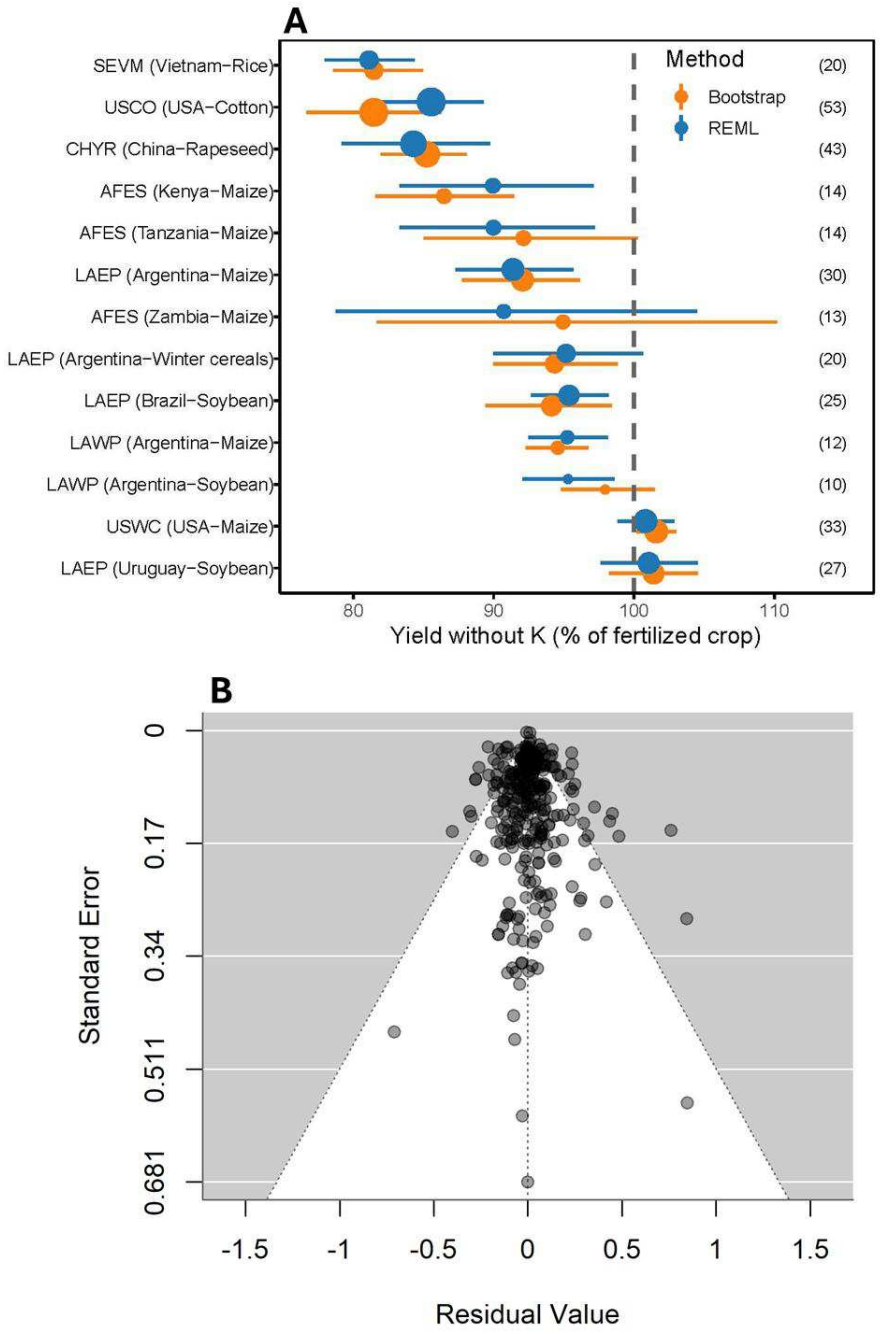
Extended Data Figure 1. Location of the 31 cropping systems included in our assessment of potassium (K) limitation to crop yields. *Colors and first two characters of cropping-system codes refer to geographic location: Latin America (LA), United States (US), South Asia (SA), China (CH), Southeast Asia (SEA), Africa (AF). Individual cropping systems are the western (LAWP) and eastern Pampas (LAEP) and associated lowland rice area (LALR); Cerrado in Brazil (LACE); Paraguay (LAPA); the western (USWC), central (USCC), and eastern (USEC) Corn Belt and Cotton Belt (USCO) in the U.S.; the Indo-Gangetic Plain in India and Nepal (SAIG), Pakistan (SAPA), and Bangladesh (SABA); eastern (SAES) and central (SACE) regions of India; North Plains (CHNP), Northeast (CHNE), Northwest (CHNW), Southwest (CHSW), and Yangtze River Valley (CHYR) regions in China; Mekong (SEVM) and Red River Deltas (SEVR) in Vietnam; lowland rice area in Myanmar (SEMY), Philippines (SEPH), Indonesia (SEID), and Cambodia (SECA); South Africa (AFSA); and eastern (AFES) and western (AFWE) regions of Africa, and associated upland (AFUR) and lowland rice (AFLR) areas. See* ***Supplementary Tables S1-S2*** *for detailed cropping systems description.*



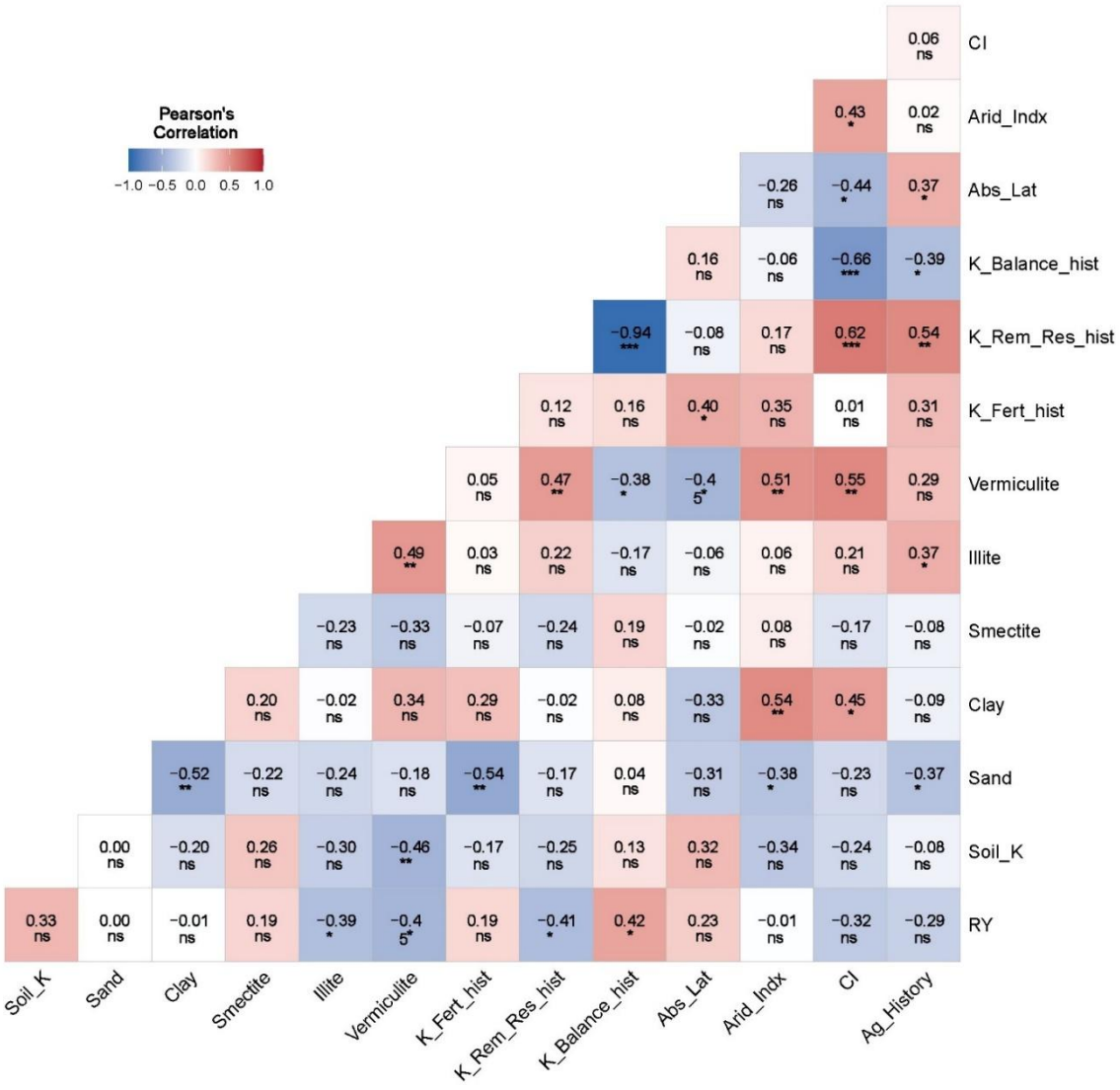
Extended Data Figure 2. Cropping intensity (CI) and main crop calendar in each cropping system. *Cropping system codes are shown in the caption to* ***Figure 1*** *and* ***Supplementary Table S1****. Location of cropping systems is shown in* ***Extended Data Figure 1****. The dotted line means the crop could or could not be planted. Abbreviations: Ct: cotton; Mz: maize; Rc: rice; Rs: rapeseed; Sb: soybean; Wh: wheat. In large regions, crop calendars can differ from those shown here.*



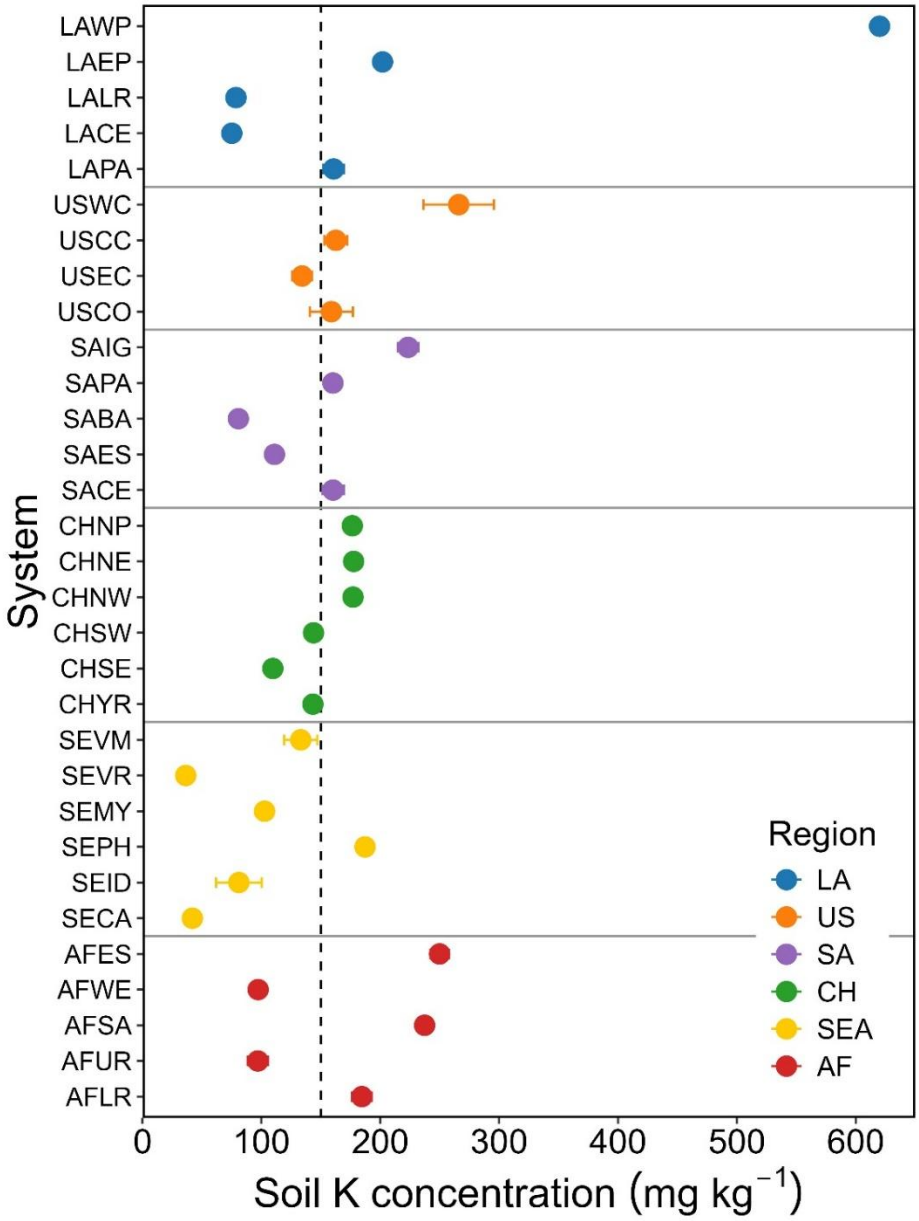
Extended Data Figure 3. Evaluation of database representativeness. *(A) Soil exchangeable potassium (K) was measured in short-term trials and producer fields based on data collected in the present study. (B) Average crop yield from field trials included in our database versus average national yields retrieved from FAOSTAT. (C) Average applied synthetic K fertilizer in farmer fields (our database) versus national averages derived from IFA; (D) average crop yields in farmer fields (our database) versus national statistics derived from FAO. Some system-crop combinations are missing due to lack of data. For China, national data was used for comparison. Cropping system codes are shown in the caption to* ***Figure 1****. Cropping systems are described in* ***Extended Data Figures 1-2*** *and* ***Supplementary Table S1****. Data are provided in Source Data.*



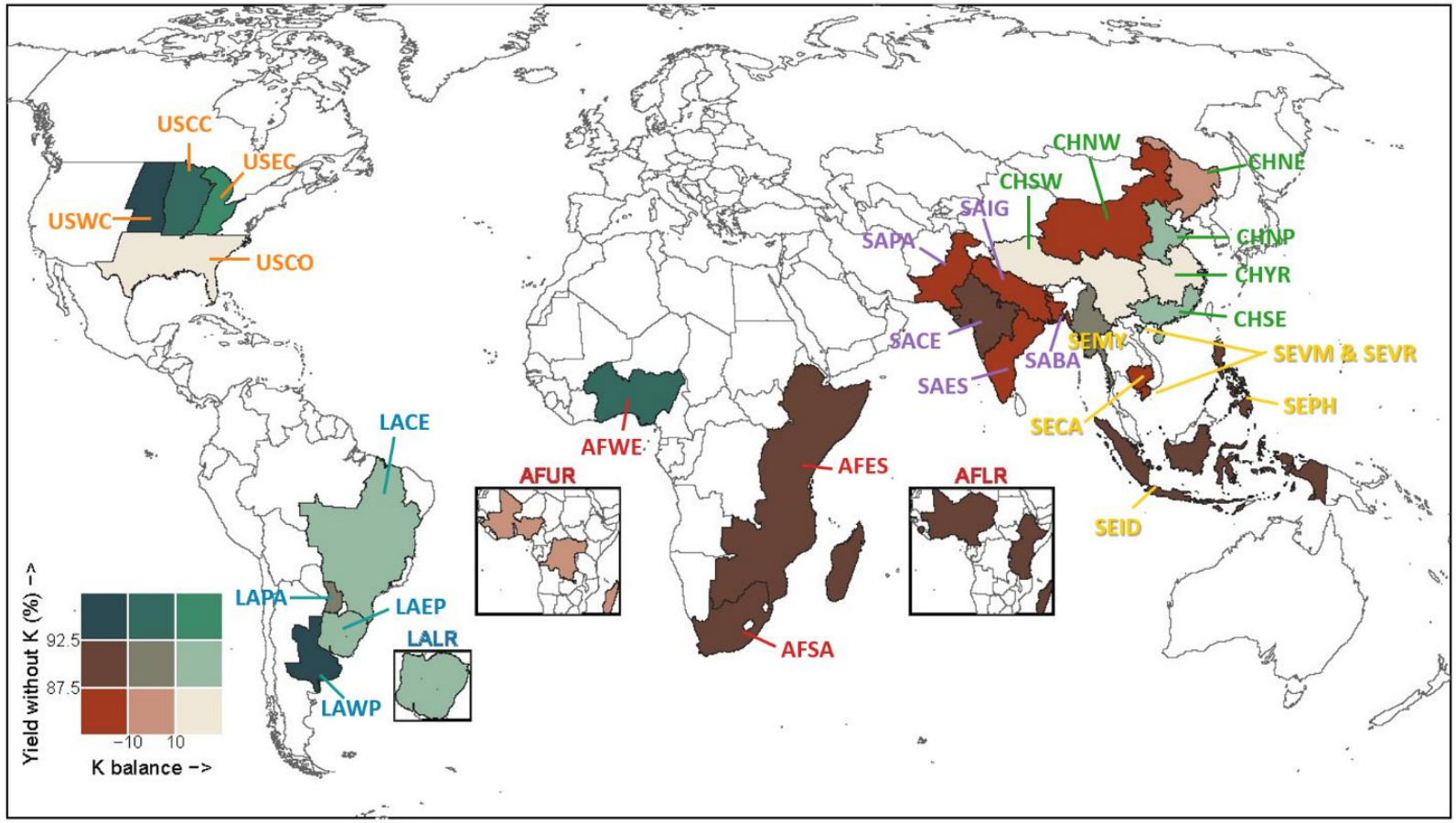
Extended Data Figure 4. Comparison of meta-analysis methods to assess K limitation (A) and funnel plot of the meta-analysis (B). *(A) comparison of the bootstrap and restricted maximum likelihood (REML) meta-analysis methods for a subsample of 13 crop-countries in which data availability allowed the comparison. (B) funnel plot to assess the presence of potential publication bias. Cropping system codes are shown in the caption to* ***Figure 1****.*



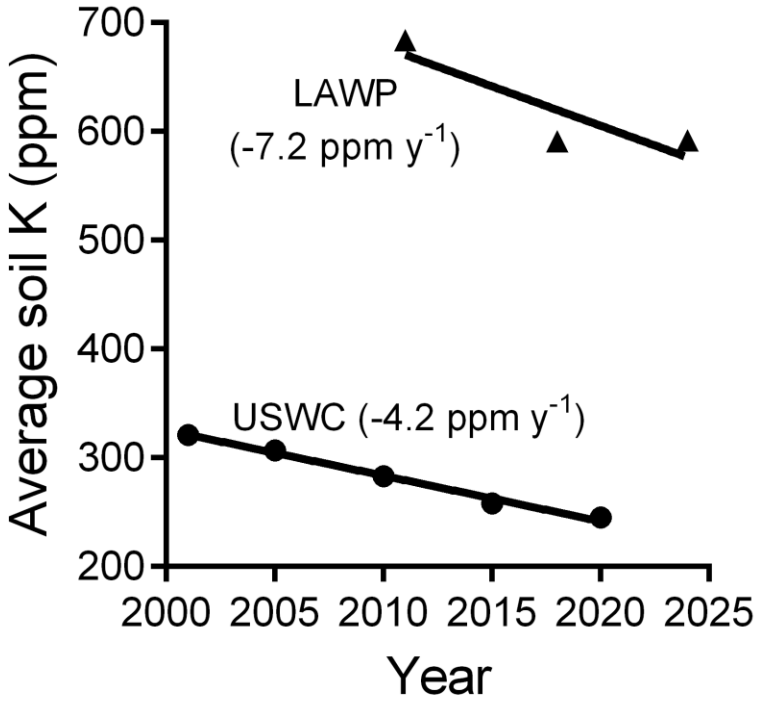
Extended Data Figure 5. Pearson correlation matrix across yield without K and soil, climate, and management variables. *RY indicates the yield of crops that did not receive K fertilizer, relative to K-fertilized crops, in field trials (see Methods, Eq. 1). Explanatory variables include soil exchangeable K in the topsoil (Soil_K), sand and clay contents, clay mineralogy (smectite, illite, and vermiculite), annual aridity index (Arid_Indx), latitude (Abs_Lat), historical K balance (K_Balance_hist), historical K inputs via fertilizers (K_Fert_hist), historical K outputs via residue removal (K_Rem_Res_hist), cropping intensity (CI), and the number of years under agriculture (Ag_History). Detailed description of variables, units, and sources are shown in* ***Supplementary Table S5****. See* ***Methods*** *for a detailed description of the statistical analysis.*



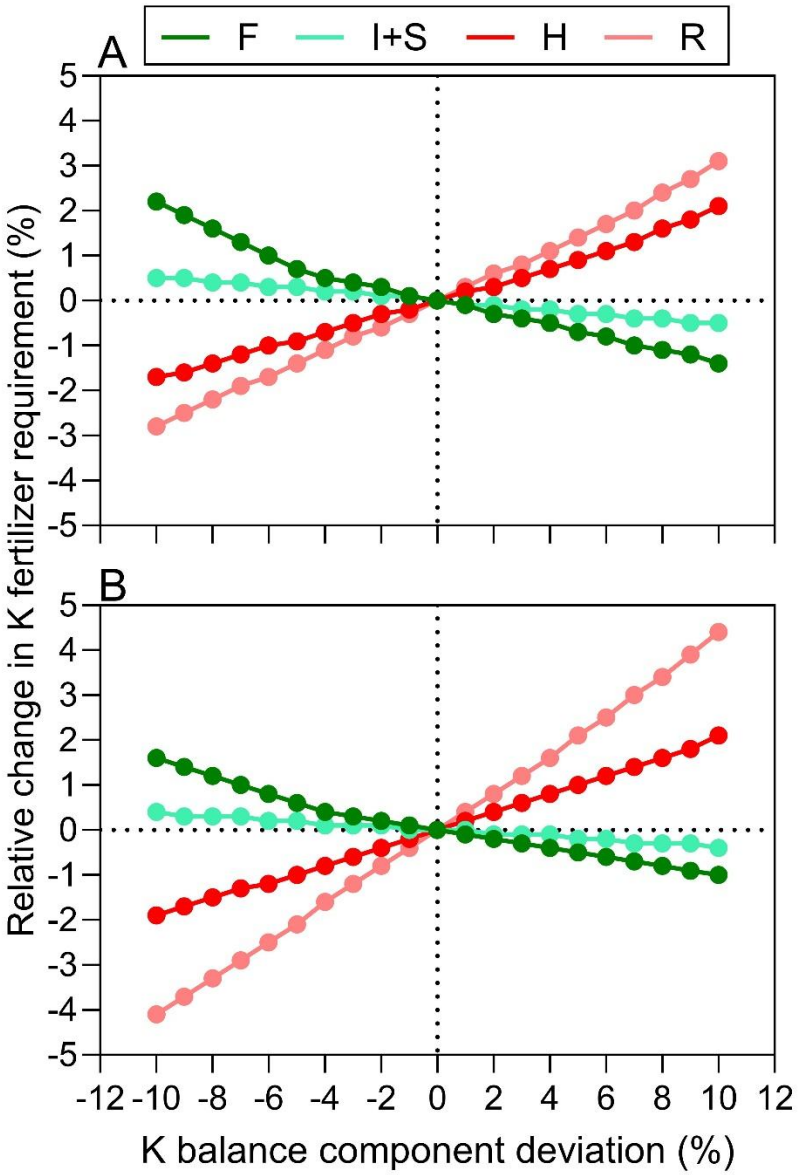
Extended Data Figure 6. Soil exchangeable K concentration across the 31 cropping systems. *Soil exchangeable K concentration was measured in the topsoil and expressed as ammonium acetate equivalent* ***(see Methods and Supplementary Figure S1)****. Means and associated 95% confidence intervals are shown with circles and horizontal bars, respectively. The latter are shown only when they do not overlap with symbols. Cropping system codes are shown in the caption to* ***Figure 1****. Cropping systems are described in* ***Supplementary Tables S1-S2****. Number of observations for each cropping system is shown in* ***Supplementary Table 6****. Data are provided as Source Data. The dashed vertical line shows the typical average soil K critical threshold of 150 mg kg^{-1} as a reference*[30]*.*



Extended Data Figure 7. Degree of potassium (K) limitation and soil K balance across the 31 cropping systems. *Map showing the 31 cropping systems, after categorization based on K limitation and soil K balance. The K limitation was quantified based on the yield from crops that did not receive K fertilizer relative to K-fertilized crops in field trials. The K balance was estimated based on K inputs from inorganic and organic fertilizers, seed, and irrigation water, and K outputs from harvested grain and residue removal and burning. Specific values of yield without K fertilizer and input-output K balance for each cropping system are shown in* ***Figure 4****.*



Extended Data Figure 8. Decline in soil potassium over time in regions with high soil potassium (K) and small K fertilizer input. *Data were collected in the Latin American Western Pampas (LAWP; n = 1,602) and U.S. Western Corn Belt (USWC; n = 3.2 million samples). Soil exchangeable K concentration was measured in the topsoil and expressed as ammonium acetate equivalent. Fitted linear regression models were statistically significant (P<0.05). Only average values for each sampling year are shown. Details on underlying data sources are provided in [24-25]. Data are provided as* ***Source Data****.*



Extended Data Figure 9. Sensitivity of estimated potassium (K) fertilizer usage to changes in K balance components. *Relative changes in K fertilizer requirement to variation in the four components of the K balance under two scenarios: zero-K balance (A) and yield intensification (B). The four K balance components include: inorganic and organic fertilizers (F), irrigation and seed (I+S), harvested yield (H), and residue removal and burning (R). See* ***Methods*** *for description of sensitivity analysis and* ***Figure 5*** *for results from the scenario assessment.*

Supplementary Files

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