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Rise in Potassium Deficiency in the US Population Linked to Agriculture Practices and Dietary Potassium Deficits

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ABSTRACT: This paper, for the first time, provides evidence that current practices that lead to agricultural crop removal of potassium are unsustainable and likely contributed to the decline in dietary potassium intake and rise in hypokalemia prevalence in the US population. Potassium concentrations in beef, pork, turkey, fruit, vegetables, cereal crops, and so forth decreased between 1999 and 2015 based on the examination of potassium values of food items of USDA standard reference. Ratios of potassium input to removal by crops between 1987 and 2014, potassium in topsoil, and crop-available soil potassium in US farms all declined in recent years. Reported reductions in dietary potassium intake correspond to these decreases in the food supply and to increases in hypokalemia prevalence in the US population. Results of this paper provide new understanding on links between potassium management in agricultural practices and potassium intake deficits, which is needed for combating increasing hypokalemia prevalence in the US population.

KEYWORDS: *potassium deficiency, hypokalemia, serum potassium, food potassium level, agricultural potassium application*

1. INTRODUCTION

Potassium (K) is the most abundant exchangeable cation in the human body and exists predominantly in the intracellular fluid.[1] It helps regulate fluid balance, muscle contractions, and nerve signals, helps reduce blood pressure (therefore, lower the hypertension rate) and water retention, protects against stroke, and prevents osteoporosis and kidney stones.[2−8] Inadequate K intake from diet in the general population has long been recognized in the US and around the world.[9−11] Recent studies also indicated that overall K intake in US adult population is still on the decline, and hypokalemia (serum K level <3.6 mmol/L, also regarded as K deficiency) prevalence is on the rise.[12−14] Recommendation for increasing K dietary intake has focused on encouraging selection of high K food items, and changes of K input in agricultural practice and resulting changes in the K level in the US food supply have largely been ignored.[9,10,12] However, recent reports show a general decline of K proportion in the total amount of fertilizers (nitrogen, phosphate, and potash) in many countries, including the US.[15−17] When long-term K removal in the soil by crop harvesting is not balanced by K addition from fertilizers and release from soil weathering, decline of K concentration in US agricultural products and food items is inevitable, given the diluting nature of nutritional elements from increasing crop yield per acre in recent decades.[18]

Most of the US food supply is domestic [US Department of Agriculture (USDA) estimated about 87.3% of food and beverages were domestic in 2016].[19] Given the worsening trend of hypokalemia prevalence in the US population and the apparently unsuccessful past efforts in pursuing high K diets to decrease K deficiency, the authors hypothesized that there has been a broad reduction of K in US food products. The authors also hypothesized that continuously rising high ratios of crop K removal/input in US farms are unsustainable and have contributed to the worsening K intake deficit in the US population in the past decades.[12,17] Therefore, the aim of this study was to relate changes in agricultural practices with the K level of food products, K intakes, and hypokalemia prevalence in the US over the time period of 1999 to 2015. The analyses used databases from the USDA standard references (SRs) for K levels of food items, the National Health and Nutrition Examination Survey (NHANES) for dietary K intake and serum K levels, and the International Plant Nutrition Institute (IPNI) for agricultural soil K levels and K input-to-removal ratios in the US.

2. MATERIALS AND METHODS

2.1. Data. K values of common US food items were obtained from the USDA Nutrient Database for SR.[20] SR11 (1999 release) contains data on 5635 food items and up to 79 food components. SR28 is the most updated version of the SR database (2015 release) containing 8789 food items and up to 150 food components. USDA SR food composition data were compiled from published and unpublished sources of varied time periods. More recent SR databases include more newly updated data (e.g., SR28 has data from 1952 to 2015, while SR11 has data only up to 1999). The data sources include the scientific and technical literature, food industry, other government agencies, and research conducted under contract with the Agricultural

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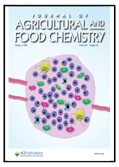

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Table 1. Average Potassium Concentrations of Food Items in the SR of 1999 (SR11) and 2015 (SR28) and Their Potassium Ratios (Grouped by Common Names)[a]

food item groups	food item counts in each group	mg/100 grams 1999 (mg/100 g)	mg/100 grams 2015 (mg/100 g)	potassium ratios of 2015/1999
Common Food Items with K Concentrations of SR28 < SR11				
beans	20	372 (±147)	358 (±158)	0.96 (±0.56)
beef	172	338 (±9)	292 (±9)	0.86 (±0.03)
candies	49	240 (±38)	215 (±37)	0.9 (±0.2)
corn	20	198 (±24)	188 (±24)	0.95 (±0.16)
egg	25	255 (±112)	253 (±113)	0.99 (±0.62)
finfish	34	379 (±29)	332 (±40)	0.88 (±0.11)
milk	32	373 (±181)	371 (±181)	0.99 (±0.68)
pork	105	350 (±15)	329 (±18)	0.94 (±0.06)
snack	17	423 (±215)	389 (±177)	0.92 (±0.6)
turkey	31	253 (±21)	216 (±17)	0.86 (±0.09)
Fruit and Vegetables				
apples	5	88 (±31)	84 (±18)	0.96 (±0.39)
apricots	3	721	611	0.85
asparagus	5	206 (±59)	199 (±32)	0.97 (±0.32)
avocados	3	574	448	0.78
bananas	1	396	358	0.90
blackberries	1	196	162	0.83
broccoli	5	254 (±85)	237 (±109)	0.93 (±0.51)
cabbage	6	154 (±63)	222 (±41)	1.44 (±0.7)
carrots	7	222 (±58)	235 (±39)	1.06 (±0.33)
cauliflower	1	303	299	0.99
figs	2	507	487	0.96
kiwi	1	332	312	0.94
melons	3	263	226	0.86
onions	1	157	146	0.93
papayas	1	257	182	0.71
pears	1	125	116	0.93
peas	6	290 (±356)	235 (±303)	0.81 (±1.31)
peppers	5	235 (±124)	235 (±76)	1 (±0.62)
plums	1	172	157	0.91
potatoes	13	416 (±131)	444 (±145)	1.07 (±0.5)
Fruit and Vegetables				
squash	9	269 (±76)	234 (±27)	0.87 (±0.26)
tomato	21	256 (±85)	281 (±94)	1.1 (±0.54)
watermelon	1	116	112	0.97
Common Food Items with K Concentrations of SR28 > SR11				
baby food	47	153 (±42)	165 (±35)	1.08 (±0.38)
cereal	107	238 (±35)	256 (±33)	1.07 (±0.22)
cheese	37	122 (±19)	133 (±20)	1.09 (±0.25)
chicken	21	210 (±15)	242 (±19)	1.15 (±0.13)
dessert	31	135 (±29)	137 (±33)	1.01 (±0.33)
fast food	39	206 (±32)	218 (±27)	1.06 (±0.22)
infant	20	270 (±99)	271 (±98)	1 (±0.51)
nuts	46	511 (±72)	538 (±72)	1.05 (±0.21)
rice	28	118 (±37)	134 (±33)	1.13 (±0.47)
soup	40	111 (±35)	136 (±48)	1.22 (±0.66)
all others	419	341 (±32)	330 (±58)	0.97 (±0.19)
Raw vs Cooked Food Items				
raw	248	293 (±20)	278 (±19)	0.95 (±0.09)
cooked	346	303 (±14)	275 (±12)	0.91 (±0.06)

[a] Food items were counted for each group only when their K concentrations are different between SR11 and SR28 for this table. They were counted by the terms appearing at the beginning of the food description except for raw and cooked where they were counted when they appear anywhere in the food description. 790 K values of food items in 2015 were smaller than those in 1999, while 653 K values in 2015 were larger than those in 1999. A total of 2848 food items remained the same. 1340 items of 1999 had no exactly matching item descriptions in 2015. A total of 25.6% of K values of all food items in 1999 were different from (or were adjusted by) 2015. Numbers in the parentheses are the values for obtaining the upper (+) and lower (−) 95% confidence range. 95% confidence range of the food item group with counts <5 was not listed. There are four sections in the table.

Research Service (ARS). Values may be analytical or calculated by the use of appropriate factors or recipes. Details about the source and year that the data were analyzed for a specific food item can be obtained from USDA Ag Data Commons site.[19] USDA data are the main data source for food composition used for dietary studies in the US.

County and state level K (estimated in tons of K_2O) use and crop removal between 1987 and 2014 were obtained from Tabular Data, Nutrient Use Geographic Information System of IPNI.[21] Data for estimating the K use (also refers as K input in the paper) from commercial fertilizers in IPNI tabular data were from the Association of American Plant Food Control Officials which collects detailed information on the county that the fertilizer was sold in.[22] K input also includes the amount of K_2O recovered from excreted livestock manure. K removal values were calculated by multiplying the estimated 3 year average production of each crop by that crop's nutrient removal coefficient for each county. Removal values for each crop were then summed together for each county to provide a total K removal value for each county.[23] Soil K concentrations of 2010 were obtained from 4856 sites at depths 0−20 cm collected by US Geological Survey (USGS).[24] USGS soil samples were collected between 2007 and 2010, and chemical and mineralogical analyses of these samples were completed in 2013. Soil K concentrations of 1976 were collected from 1218 sites at a depth of approximately 20 cm and analyzed by the USGS between 1961 and 1976.[25]

Daily dietary K intakes in mg/day of 39,104 men and 40,164 women aged 0−80 years old between 1999 and 2016 (~10,000 each 2 yr cycle) were obtained from the NHANES dietary interview—Total nutrient intake, first day file.[25] The files contain the nutrient intake values of participants based on their recall of food and beverage consumed during the 24 h period prior to the interview. They were administered in person in a Mobile Examination Center (MEC) by NHANES. Nutrient values were assigned to foods by using the USDA Food and Nutrient Database for Dietary Studies corresponding to each 2 year phase.[26] Daily dietary K intakes of individuals were estimated by summing the K consumed from each food or beverage reported for that day. K intakes reported in these files do not include those obtained from dietary supplements, medications, or plain drinking water. It also needs to be noted that variations of K concentration in SR codes from different years can affect the consistency of dietary K estimation and comparison. Serum K data in mmol/liter were obtained from the Standard Biochemistry Profile files of NHANES measured between 1999 and 2016 for 27,826 men and 28,975 women and were used in our previous hypokalemia trend study.[17] Blood samples were collected from participants administered in the MEC by NHANES, and the standard biochemistry data of participants (~6000 each 2 yr cycle), including K ion concentration, were measured in NHANES-designated laboratories. The analyzed data contained nine NHANES sampling cycles between 1999 and 2016 because NHANES data are released once every other year. Age, gender, race, interview, and MEC sample weight data were obtained from the demographic files in the NHANES database.[26]

NHANES is a program of studies intended for assessing the health and nutritional status of adults and children in the US, administered by the National Center for Health Statistics (NCHS) of the US Centers for Diseases Control and Prevention. The population was sampled with a complex, stratified, multistage probability cluster sampling design to provide data that are nationally representative of the civilian, noninstitutionalized US population. Participants provided written informed consent before participation. Detailed descriptions of the survey design and data collection procedures are available in NHANES documents.[26] NHANES data collection was reviewed and approved by the NCHS ethics review board.[27]

2.2. Statistical Analyses. Only matched food items (identified by description code NDB_NO) of 1999 SR11 and 2015 SR28 were examined, and only food items with K values in SR11 being either larger or smaller than those in SR28 were used for comparison. Food items in SR11 with K values being the same and having no matching ID code in SR28 were not used for comparison. Food items with common names such as beef, pork, turkey, chicken, bean, corn, and so forth that appear as the first term in the food description of 1999 SR11 and 2015 SR28 were grouped by these common names. The averages and 95% confidence intervals (CIs) of K values in each food group of 1999 SR11 and 2015 SR28 and ratios of average K values of each group of the 2 years were calculated. In addition, K values of most of fruits and vegetables (as a separate category) listed in the 2 years were compared as well. Two additional separate food group categories of "raw" and "cooked" in SR11 were also created when either term appears anywhere in the matched food description and only when K values in SR11 are either larger or smaller than those in SR28.

K uses from fertilizer and manure and crop removals of 1987, 1992, 1997, 2002, 2007, 2010, 2011, 2012, 2013, and 2014 were summarized from 3109 counties in the 48 US states based on IPNI data.[21,22] Their mean ratios, standard errors, and 95% CIs were calculated in Stata (SE/14) using its Ratio tool in Summary and Descriptive Statistics. Only the county level soil K data of 2010 and 1976 were estimated from the USGS analytical soil K point data of the respective year by inverse distance-weighted interpolation method and zonal statistics as a table tool in ArcGIS (ESRI, version 10.7). Choropleth maps of soil K level in 2010, changes of topsoil K from 1976 to 2010, and average ratios of farm K use to crop removal between 1987 and 2014 for 3109 counties in the 48 US states were plotted to examine the county level K changes in the US farm soil.

Weighted sample means and their 95% confidence intervals of the dietary intake of the first 24 h food recall data were stratified into adult and nonadult men and women for the nine data cycles between 1999 and 2016. Ages 0−17 were considered as nonadult minors, and ages 18−80 were considered as adult in the calculation. A total of 22,409 adult men, 23,895 adult women, 15,733 men minors, and 15,379 women minors were tallied for the dietary data. Data from participants of age 81 and above were excluded because data from this age group were not collected after the 2003−2004 cycle. Weighted means, standard errors, and their 95% confidence levels of serum K of 27,826 men and 28,975 women grouped by sex were calculated. Respective sample weights (interview and MEC from the demographic files) were used to account for differential nonresponse and/or noncoverage to adjust for planned oversampling of some groups and to adjust for uneven representation of days of the week. Average hypokalemia (serum K level <3.6 mmol/L) prevalence of men and women corresponding to the means of four dietary K intake quartiles were calculated for 27,826 men and 28,975 women and stratified into adult (ages 18−80) and nonadult (ages <18). Nonparametric Kendall's tau_b correlation of mean quartiles of K intakes and corresponding hypokalemia prevalence rates were calculated as well. Statistical analyses, including weighted means, proportions, correlations, standard errors, 95% CIs, and linear regression trends of all NHANES data, were conducted in Stata (SE/14) using its Survey Data Analysis tool. Data processes requiring only sorting and simple calculations were conducted in Microsoft Excel.

3. RESULTS

3.1. Decrease of K Concentration in US Food Products. Among 5631 food items in the USDA SR11 release in 1999, 1443 food items (25.6%) had codes that were different from those in the SR28 release in 2015, 2849 food items (50.5%) were identical, and 1339 food items (23.8%) had no exact match (i.e., no identical food code) in SR28 (Table 1). Among the 1443 food items that had different K concentration values, 790 food items (54.7%) had lower K concentrations in 2015 than in 1999, while 653 food items (45.3%) had higher K concentrations. The food item group having lower K concentrations in 2015 than in 2011 included beef, pork, turkey, corn, beans, and so forth. Most of the fruits and vegetables also have lower K concentrations in 2015 SR28 than in 1999 SR11, and their average K ratio of 2015−1999 SR11 is 0.934 (CI 95% ± 0.032). Food items with lower K concentration in 2015 contain relatively less processed food and have higher (dense) K concentrations per 100 g. The food items having higher K concentrations in 2015 than in 1999 include cereal, baby food, soup, and fast food; they have more highly processed food items and may have K added in (Table 1). K concentrations in both cooked and raw food items decreased from 1999 to 2015 with more significant decreases in cooked food items.

3.2. Decreasing Dietary K Intake and Serum K Concentration in US Population. There are significant declining trends in the K intake of men of all age groups (significant level p of slopes of all trendlines <0.01) in the US population and for women of all age groups ($p < 0.01$), except age group of 41−60 between 1999 and 2016. The declining trends of averaged K intake are only apparent among the two younger age groups 0−20 and 21−40 (Figure 1). When the age groups are grouped only by adult and nonadult categories, the declining trends of K intakes are still significant for both men and women between 1999 and 2016 (Table 2). Declining trends of serum K levels between ages 12 and 80 for both sexes are also apparent between 1999 and 2016 (Figure 2). Details of serum K decline during this period were reported in our previous study.[17] Men's K intake and serum K levels are consistently higher than those of women.

3.3. Low K Intake Corresponds to High Hypokalemia Prevalence. There are significant inverse correlations between mean quartiles of K intake and prevalence of hypokalemia for both adult men and women (ages 18−80 years) (Table 3). For adolescents (12−17 years), there is a general inverse relationship between increase of K intake and decreasing hypokalemia prevalence for both sexes. However, they are not statistically significant (for nonparametric

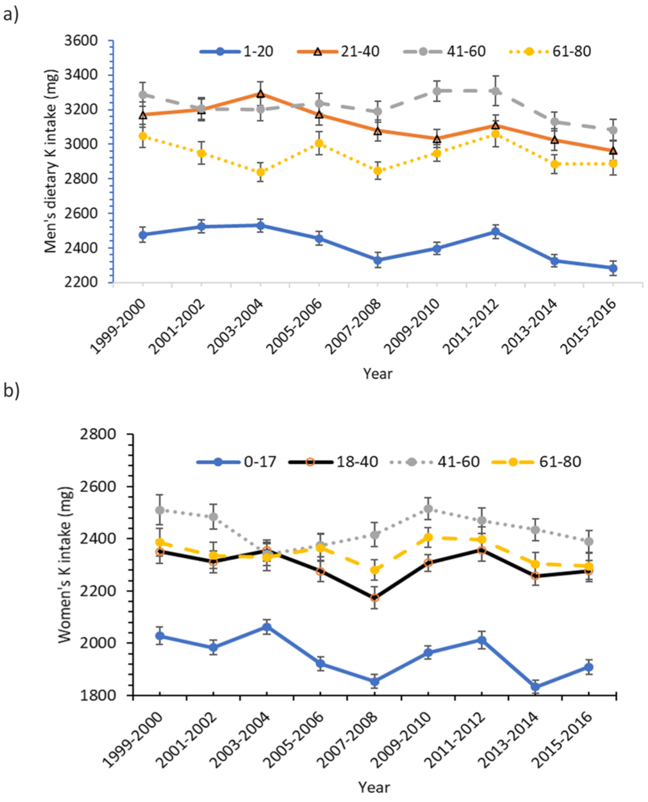

Figure 1. Trends of age-stratified average 24 h dietary potassium intake for (a) 39,104 men and (b) 40,810 women between 1999 and 2016. Vertical bars show the standard errors. Numbers in legends are age ranges.

Table 2. Average 24 h K Intakes (mg) of the US Population between 1999 and 2016[a]

	men		women	
year	ages 0−17	18−80	ages 0−17	18−80
1999−2000	2355 (±79)	3171 (±82)	2029 (±64)	2413 (±60)
2001−2002	2391 (±67)	3157 (±74)	1984 (±54)	2384 (±55)
2003−2004	2383 (±71)	3169 (±76)	2063 (±56)	2345 (±52)
2005−2006	2338 (±75)	3149 (±70)	1922 (±50)	2331 (±52)
2007−2008	2194 (±81)	3055 (±68)	1853 (±52)	2290 (±50)
2009−2010	2274 (±69)	3105 (±62)	1964 (±49)	2405 (±43)
2011−2012	2316 (±70)	3172 (±83)	2012 (±64)	2408 (±53)
2013−2014	2220 (±67)	3004 (±65)	1833 (±49)	2332 (±46)
2015−2016	2206 (±81)	2969 (±69)	1909 (±55)	2322 (±50)

[a] Participants aged 0−17 are considered minor and ages 18−80 are considered adults. Numbers in the parentheses are the values for obtaining the upper (+) and lower (−) 95% confidence range.

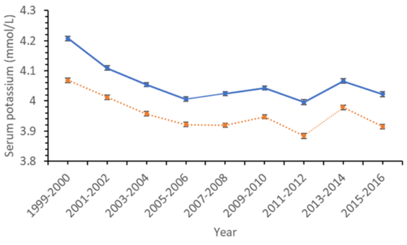

Figure 2. Average serum K levels of men and women aged 12−80 in the US between 1999 and 2016. Vertical ticks show the small standard errors.

Table 3. Quartiles of Average Daily K Intake and Their Corresponding Average Hypokalemia (K < 3.6 mmol/l) Prevalence in Adolescents and Adults of the US Population between 1999 and 2016[a]

K intake quartiles	ages 12−17		ages 18−80	
men	mean intake (mg)	hypokalemia (%)	mean intake (mg)	hypokalemia (%)
1st	1131 (±27)	3.6% (±1.6%)	1464 (±14)	7.6% (±1.0%)
2nd	1970 (±15)	2.6% (±1.9%)	2377 (±8)	5.9% (±0.9%)
3rd	2756 (±20)	2.6% (±1.4%)	3189 (±9)	4.6% (±0.8%)
4th	4457 (±97)	2.1% (±1.3%)	4824 (±40)	4.3% (±0.8%)
women	ages 12−17		ages 18−80	
1st	921 (±21)	7.2% (±2.6%)	1151 (±10)	14.0% (±1.2%)
2nd	1561 (±13)	6.5% (±2.6%)	1870 (±6)	10.2% (±1.0%)
3rd	2150 (±15)	4.9% (±2.2%)	2521 (±7)	9.3% (±1.0%)
4th	3310 (±55)	5.8% (±2.4%)	3730 (±27)	8.0% (±1.0%)
correlation	K intake vs hypokalemia age 12−17		K intake vs hypokalemia age 18−80	
men	0.667 (p = 0.134)		−1 (p = 0.00)	
women	−0.667 (p = 0.134)		−1 (p = 0.00)	

[a] First quartile has the lowest K intake, the fourth quartile has the highest K intake, and so forth. Numbers in the parentheses are values for obtaining the upper (+) and lower (−) 95% confidence range. There are 5228 men between ages 12 and 17; 21,201 men between ages 18−80; 4987 women between ages 12 and 17; and 22,455 women between ages 18 and 80. p in the parentheses is the nonparametric Kendall's tau_b correlation significance level of mean quartiles of K intake versus hypokalemia, and $p < 0.05$ indicates correlation is significant with 95% confidence.

Kendall's tau_b test, both correlations $r = -0.667$, $p = 0.134$). Increases in hypokalemia prevalence with decreased K intake is more striking in the lower K intake quartiles.

3.4. Declining Ratios of K (K_2O) Input to Crop Removal in US Farms and Depletion of Soil K. Decline in ratios of K input to K crop removal between 1987 and 2014 is steady (Figure 3). On average, the ratio of K mass input to removal is 0.72 (±0.026) between 1987 and 2014, and this is an average of 28% more K being removed than added in US farms between 1987 and 2014. K input/crop removal ratios declined in about 70% of the counties (2107 counties out of 3045 counties with data in both years) between 1987 and 2014 in the 48 US states. In 2014, 72.9% of the counties (2230 out of 3060 counties with data) in the 48 US states have K usage deficits in the US (crop removal larger than input from fertilizer and manure). When county level K weight percentages in topsoil (0−20 cm depth) of the 48 states

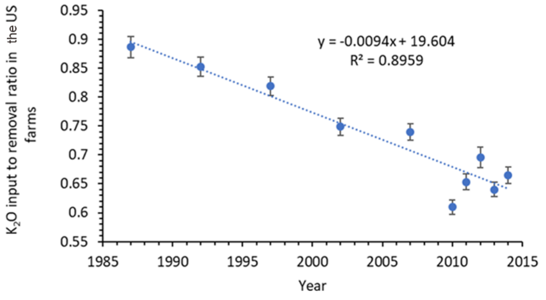

Figure 3. Ratios of total potassium fertilizer input to crop removal in farms of the 48 US states between 1987 and 2014. Vertical bars show the standard errors.

between 1976 and 2010 were compared, approximately 63% of the counties had lower K weight percentages in 2010 than in 1976 (Figure 4).

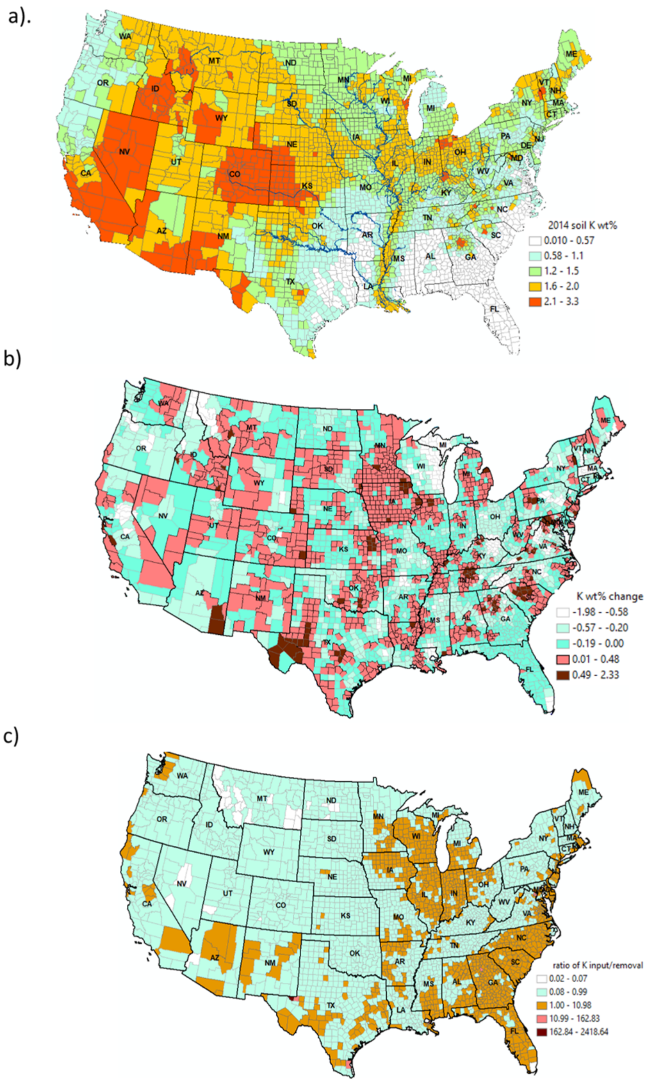

Figure 4. (a) K weight percent (wt %) in topsoil (≤20 cm depth) of 2010. Note the lowest K wt % mainly in the southeast US. (b) Weight % change (result of subtraction) of topsoil in the 48 US states from 1976 to 2010. (C) Average ratios of farm K input to crop removal between 1987 and 2014. Seventy percent of the US counties' K farm input was lower than crop removal (ratio <1 in plot) between 1987 and 2014 and 63% of the US counties' topsoil K declined (K wt % change <0 in plot) from 1976 to 2010.

4. DISCUSSION

4.1. Decline of K Level in US Food Items, Dietary K Intake, and Serum K Levels in US Population. For the approximately 25.6% of total food items in 1999 (USDA SR11) with different K levels from those in 2015 (USDA SR28), 54.7% of the food items had lower K concentrations in 2015 (Table 1). The food item groups with lower K concentrations in 2015 than in 1999 include beef, pork, turkey meat, beans, corn, and so forth, and they are the food items not formulated with K salts. K changes of food groups not fortified with K salts better reflect the K changes of US agricultural products than fortified foods. K levels in most fruits and vegetables in 2015 SR28 were also generally lower than those in 1999 SR11 (Table 1), and the group average was significantly lower in 2015 S28 than in 1999 SR11 (average K ratio of 2015 to 1999 is 0.934 with 95% CI ± 0.0327). This result is consistent with the significant declines of average K concentrations in fruits and vegetables from 1941 to 2004 reported for US horticultural products.[28,29] Similar declining trends of K were reported in British fruits and vegetables as well.[30] Food categories of protein, grain, vegetables, fruits, and mixed dish (pizza, sandwich, and other dishes) together contribute more than 65% of the total K dietary intake in US population.[31,32]

K dietary intakes between 1999 and 2016 were all considerably lower than the recommended intakes, and the trend is getting worse (Table 2). The worsening trend corroborates the K decline previously reported from year 1988−1999 to 2003−2008 in US adults.[12] Declining trends of serum K levels[17] are more apparent than the declining trend of dietary K intakes (Figure 2). Hypokalemia prevalence in US population was reported to have increased from 4.37 to 12.31% between 1999 and 2016 with higher rates in women than in men.[16] The clear inverse relation between K intake and hypokalemia prevalence (Table 3) reflects the influence of K dietary intake on serum K levels and hypokalemia prevalence in the US population. Because only 25.6% of food items in 2015 was different from those of 1999 while all food items were used in the calculation of K dietary intake, it is possible that the actual dietary K intakes were lower than the current data shown if K levels of more food items were remeasured during this period. Sex and age differences in the 24 h K dietary intake (Figure 1) likely reflect the different amounts of food (calories) intake and varied food selection of men and women during different age periods.[33,34]

Given that most of the US food supply (∼87.3% of food and beverage being domestic in 2016)[32] is domestic, declining K levels in US agricultural products can inevitably lead to decreased dietary K intake, reduced serum K levels, and increased hypokalemia prevalence across all age groups of people in the US. Changes in dietary preferences such as declining fluid milk consumption from 1977−1978 to 2005−2006 may have also contributed to the decline in dietary K intake in the US.[35,36]

4.2. Causes of K Reduction in US Food Products and Low Crop-Available Soil K. K is one of the most readily leachable, if not the most leachable and erodible nutrient elements in soil because of its reactive chemical property.[37] The monovalent and electropositive property of K makes it readily soluble in water because of the polarity of water molecules. With persistent weathering, there will be a natural loss of soil K through time in areas with high precipitation, temperature, and bioactivity. This is evident by the lowest K level in the topsoil of the southeastern US where precipitation, temperature, and bioactivity are the highest in the continental US (Figure 4a). Though this is a rough estimation, K in the topsoil was lower in approximately 63% of the counties in the 48 US states in 2010 than in 1976 based on the interpolation of spot soil K data across the 48 states by the USGS (Figure 4b). In agricultural farms, in addition to leaching from precipitation runoff, K loss is aggravated by irrigation water runoff and crop removal.[37] Unless K loss in farm soils can be compensated by K gain from rock weathering and application of K fertilizer and manure, there will be a net loss of plant-available soil K overtime. On average, higher crop K removal than K input was observed in about 70% of the counties in the 48 US states between 1987 and 2014 (Figures 3 and 4). K application proportion of nitrogen, phosphate, and potash (K_2O) was on a steep decline in the past 50 years in the US primarily because of its low yield benefit.[17,38] Previous studies have suggested that nutrient dilution can be related to the continuous selection of high-yield cultivars in agriculture practice.[18] IPNI data also indicate that crop-available soil K level declined in most of the US farming states between 2010 and 2015.[17,39] Declining crop-available soil K, in addition to K dilution because of the increasing yield per acre of crops, will inevitably result in an overall K reduction in most crop products, including forage, grains, and meat (result of grazing lower K feed and hay) in the US.

4.3. Measures that Might be Taken to Reduce K Deficiency. The strong inverse relation between quartiles of K dietary intake and hypokalemia prevalence indicates that increasing dietary K intake can correct the K deficiency (hypokalemia) in the US population. In addition to encouraging intake of a high K diet, increasing K in agricultural products including grains and meats is also necessary. This will call for improvement in soil K management in the US through reducing soil K loss from leaching and erosion and increasing K application of fertilizer and manure. Improvement in overall K levels in animal feeds (so that K level in meat can increase) might need to be examined as well. In addition to selection of high K food items, improvement in preservation of K during food processing such as skin removal, boiling, and cooking can help reduce the K loss from food.[14,17] Because of the association of K deficiency with many health issues and the worsening K deficiency trend,[2−5,17] restoring K level in US food products may need to be brought to the level of national nutritional safety.

There are a few limitations for this study that need to be mentioned. Procedures for K concentration measured in soil by USGS and in food items of SR11 and SR28 by USDA varied among data sources and across years, and these variations can result in inconsistency in their reported K concentrations. County level soil K was obtained through data interpolation in the ArcGIS which can introduce estimation errors. Possible errors can be introduced during the NHANES sampling (including errors in dietary recall) and laboratory measurement.[40] Also, dietary K intakes and serum K levels in the NHANES database were from a one-time measurement. Estimation and comparison of dietary K intakes from different time periods can be affected by the K levels of SR codes of a particular year. At a population level, low K intakes contribute to hypokalemia prevalence, but at an individual level, hypokalemia diagnosis may not reflect an individual's low K intake but may reflect an excessive K loss in urinary excretion or stool.[41,42] Agricultural K management and relation to K levels in the US food supply need to be further studied.

In summary, we think that decline of K level in food items from 1999 (SR11) to 2015 (SR28), including beef, pork, turkey, fruits, vegetables, corn, bean, and so forth, reflects changes of K levels in the US agricultural products. The declining ratios of K input to crop K removal between 1987 and 2014 and the declining crop-available soil K in the past contributed to the lower K concentrations of more recent food products in the 48 US states. Given that most US food and beverage supplies are domestic (87.3% in 2016), declines of K levels in US food products likely contributed to the decline of dietary K intake between 1999 and 2016. Decreasing dietary K intake corresponds to decreasing serum K levels and rising hypokalemia prevalence in US population between 1999 and 2016. The worsening trend of low K dietary intake and rising hypokalemia prevalence in US population calls for a renewed effort for encouraging high K diet and agricultural policy initiatives to increase the K level in US food products. Better soil management of K loss, increasing application of K fertilizer and manure, and improvement of K levels in animal feeds might be effective initiatives.

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Notes

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