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ORIGINAL ARTICLE

Assessment of potassium soil balances and availability in high yielding rice systems

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Abstract Plant demand for K in rice is comparable to nitrogen. With yields and management practices changing, refining K fertility management and decision-making tools is necessary. Our objectives were to determine (1) how soil K balances affect soil K indices, (2) the best soil test indicator of plant K availability, and (3) the relationships between plant and soil K indices. We assessed soil (plow layer) and flag-leaf samples from 55 commercial rice fields in California. Growers provided historical information on K fertility practices, straw management, and yields to develop a soil K balance. A soil K balance average of −15 kg K ha^{-1} yr^{-1} (range: −72 to 47) suggested an increased likelihood of K infertility; however, K balance was not correlated with soil K indices or flag-leaf K. This, plus the potential for K losses and fixation of surplus K, suggests that attempting to build up soil K may not be an effective strategy. Soil K indices were poorly correlated with plant K, but 1 N NH_4OAc-extractable K (Kext) was the best of the K indices tested. Soils that were low in Kext had low clay content, CEC, and K saturation, a high Ca + Mg:K ratio, and showed evidence of K fixation. Soil K varied regionally and may be related to irrigation water and soil parent material. The critical level for Kext (currently 60 mg K kg^{-1}) may need to be revised based on our findings, as there was evidence of K deficiencies above this concentration.

Keywords Rice · Potassium · Indices · Nutrient balances · Deficiency

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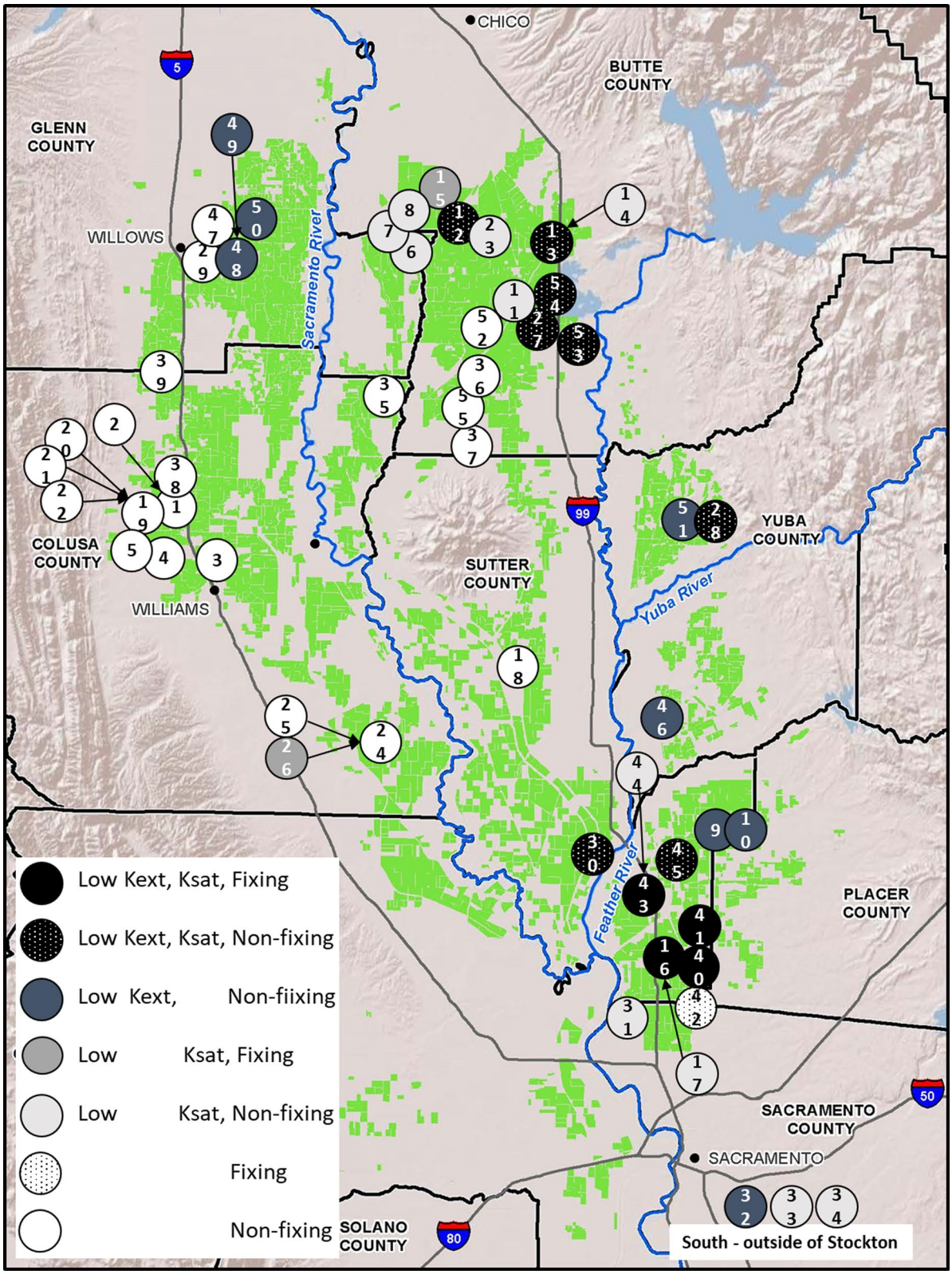
Introduction

In rice (*Oryza sativa* L.), potassium (K) has many essential functions, including osmoregulation, enzyme activation, and stomatal function (DeDatta and Mikkelsen 1985). When soils are deficient in K, plant biomass and yields are reduced, disease incidence increases (Linquist et al. 2008; Williams and Smith 2001), and there is a greater potential for lodging (Kono and Takahashi 1961).

Plant demand for K is comparable to nitrogen demand in terms of total seasonal uptake; and on average, 17 kg K are taken up by the crop for every ton of grain yield (Dobermann and Fairhurst 2000; DeDatta and Mikkelsen 1985). However, unlike nitrogen, which is mostly in the rice grain at harvest, only 15–20% of the K is in the grain; the remainder is in the straw. Therefore, grain harvest has a relatively small effect on soil K balances; while straw management can have a large effect on soil K balances and the sustainability of the system. Fertilization with K


CHICO
BUTTE COUNTY
GLENN COUNTY
WILLOWS
Sacramento River
COLUSA COUNTY
WILLIAMS
SUTTER COUNTY
YUBA COUNTY
Yuba River
Feather River
PLACER COUNTY
SACRAMENTO COUNTY
SACRAMENTO
SOLANO COUNTY
5
99
80
50
Low Kext, Ksat, Fixing
Low Kext, Ksat, Non-fixing
Low Kext, Non-fiixing
Low Ksat, Fixing
Low Ksat, Non-fixing
Fixing
Non-fixing
South - outside of Stockton

◂**Fig. 1** Map showing locations of fields in the Sacramento Valley. Numbers refer to those in Table 1. The different shade of circles indicate if fields (mean of all samples from the field) have low soil extractable K (Kext < 120 mg kg^{-1}) or low K saturation (Ksat < 1.6%) and if the soil is a fixing or non-K fixing soil. In all cases where fertilizer K was applied, flag-leaf K values were > 1.2%. At sites that did not receive fertilizer K, at the following sites flag-leaf K values were < 1.2% in at least one of the field checks tested:16, 41, 43, 49, 52 and 53

has not been common in many rice-producing regions around the world. However, without K fertilization and with increasing yields, K balances will be negatively affected and K deficiencies are expected to become more common (Dobermann et al. 1996a).

In the soil, K is present as: (1) soil solution K, (2) exchangeable K, (3) fixed K in interlayer minerals and, (4) matrix K in rocks and minerals (Barber 1995). Solution and exchangeable K are readily plant-available, but make up only a small fraction of the total K (DeDatta and Mikkelsen 1985; Bell et al. 2021a). Potassium fixation occurs when K is held in highly charged sites in the interlayer region of some layer-silicate minerals, such as vermiculite, smectite and mica. As granitic parent materials weather, primary mica minerals weather into secondary minerals, such as vermiculite and smectite. These minerals often further weather into kaolinite and gibbsite (O'Geen et al. 2008). Minerals vary in their capacity to fix K, with vermiculite having high fixation potential, while kaolinite and gibbsite have little to no fixation potential (Bouabid et al. 1991). The Sacramento Valley, where most of California rice is grown, lies just north of the San Joaquin Valley (Fig. 1). The Cascade and the Sierra Nevada ranges border the Sacramento Valley on the east, and the Coast Range borders on the west. The San Joaquin Valley is bordered on the east by the Sierra Nevada and on the west by the Coast Range. Coast Range-derived soils often have high Kext and little or no K-fixation, while the Sierra Nevada-derived soils containing granitic alluvium generally fix K (Murashkina et al. 2007a). In the San Joaquin Valley, K fertilizer requirements are higher in K-fixing soils than in non-fixing soils (Cassman et al. 1990). However, K-fixation and K fertility requirements have not been studied in the Sacramento Valley. Mikkelsen and Hunziker (1971) reported more K-deficient soils on the eastern side of the Sacramento Valley, but this has not been linked to K-fixation in these soils.

In California, rice yields are among the highest in the world. Rice yields have been increasing in California and have averaged 9.5 t ha^{-1} over the past 10 years (USDA 2021). Not all farmers apply K fertilizer, but for those that do, average rates are 28 to 40 kg K ha^{-1} (Hartley and van Kessel 2003; Williams 2010). Historically, rice straw was burned following harvest; however, in the 1990s, straw burning was restricted and most farmers began incorporating rice straw during the winter, then flooding fields to accelerate rice straw decomposition (Linquist et al. 2006). In these systems, straw K is thought to be conserved within the field. Assuming an average yield and that there is 2.5 kg K per ton of grain (Dobermann and Fairhurst 2000), 24 kg K ha^{-1} is removed in the grain at harvest. Thus, for those farmers applying K fertilizer and assuming the only K lost is via grain K removal, the K is balanced in the system. However, many California farmers do not apply K fertilizer, similar to farmers globally. As for other farmers around the world, farmers may not apply K because soils are high in clay and there are plenty of reserves, the irrigation water may contain K, and there are no visible deficiencies of K (Dobermann et al. 1996a). At question is if the higher yields (and thus greater K removal) might be increasing the likelihood of K deficiencies. Furthermore, there is increasing interest in off-site uses for rice straw. Removing rice straw would result in a large removal of K from the system as straw contains, on average, 14.5 kg K ton^{-1} (Dobermann and Fairhurst 2000).

Determining K deficiencies can be done through soil or plant analysis. While plant analysis is a good indicator, it is challenging to address the issue in the current season due to the time it takes to sample and analyze plant tissue. There are many soil analyses that have been used for rice. The 1 N NH_4OAc-extractable is the most common globally, and is also used widely in California (Dobermann and Fairhurst 2000; Williams 2010). Other soil K tests that are used for rice include K saturation (as a percent of total CEC), 1 N HNO_3, and Mehlich III (Dobermann and Fairhurst 2000; Slaton et al. 2009). In California, the currently recommended critical soil Kext concentration for California rice soils is 60 mg K kg^{-1} (Williams 2010). Dobermann and Fairhurst (2000) suggested a critical value of 78 mg K kg^{-1}, but also suggested that this value may be higher for high yielding (> 8 t ha^{-1}) rice systems, such as those in California (USDA 2021).

Given the changing yields and management practices in these rice systems, our broad objective was to identify areas where K fertility management practices and decision-making tools need to be refined. Specific objectives were to determine first, how soil K balances affect various soil K indices. Given the changing yields and management practices, we hypothesized that higher yields and increased K removal would lead to more negative K balances and lower K availability. Second, to determine which soil K index was the best indicator of K availability based on the relationship between various K indices and a measure of plant K. Finally, we wanted to examine the relationship between plant and soil K indices. While this final objective relates to objective two, we were particularly interested in the role of soil K fixation on plant K availability which has not been determined in these rice soils.

Methods

Overview

Field studies were carried out during the 2012 and 2013 rice growing seasons in California, USA. A total of 55 rice fields were involved in the study: 31 in 2012 and 24 in 2013. Selected fields represented typical climate, soil, and management practices in California. Potassium fertility and straw management practices were not criteria in selecting fields. Fifty-two fields were located in the Sacramento Valley; three were located south of Sacramento Valley, in the northern part of the San Joaquin Valley near Stockton (Fig. 1).

In California, medium grain rice is the dominate rice type grown and this is commonly grown in a water-seeded system. Typically, soil tillage begins in March, and in late April/early May the seedbed is prepared. Aqua-NH_3 is the most common N fertilizer source (Linquist et al. 2009) and is applied by injecting 70–100 mm below the dry soil surface. After this, the field is flooded and soaked seed (24–48 h) is broadcast (average about 180 kg seed ha^{-1}) by airplane. If other nutrients are applied, it is usually an N-P or N-P-K blend, which may contain S and some micronutrients. This can be applied either before flooding, or delayed and aerially applied 20 to 30 days after seeding to avoid algae build up (Lundy et al. 2012). At mid-season (panicle initiation), farmers assess crop N status and may aerially apply a top-dress N application as urea or ammonium sulfate if deficiency symptoms are apparent (Rehman et al. 2019). Following harvest in the fall, the rice straw residue is most commonly incorporated into the soil and flooded during the winter fallow period to promote straw decomposition (Linquist et al. 2006). Straw may also be baled or burned. Fields sizes vary, but average roughly 35 ha. Most fields are precision leveled and separated into basins (also called paddies or checks) using levees with weirs to facilitate water movement and maintain uniform water heights across the field. A single field may contain four to eight basins.

Soil sampling and analysis

In most fields, soil and plant samples were taken from the top, middle, and bottom basins. In one field, there were only two basins, so each basin was sampled; in two fields there was only a single basin, so only one sample was taken. Samples from each basin were kept as unique samples; thus, in total, there were 160 samples from 55 fields. The soil samples were collected in the spring prior to fertilization, but after the field had been tilled. In each basin, soil samples from the plow layer (about 0–150 mm) were taken from eight to 10 locations across the basin and pooled for that basin. After sampling, the samples were air-dried and passed through a 2-mm sieve for analysis.

Soil samples were sent to the UC Davis Analytical Laboratory for analysis of soil pH (saturated paste U.S. Salinity Laboratory 1954), soil organic carbon (Nelson and Sommer 1996), texture (Sheldrick and Wang 1993) and ammonium acetate (NH_4OAc) extractable K (Kext; 1 M NH_4OAc at pH 7; Thomas 1982). The soil K fixation potential (Kfix) was determined using the method developed by Cassman et al. (1990) and modified by Murashkina et al. (2007a). In brief, each soil sample was done in triplicate. Three g of soil were shaken for 1 h with 30 mL 2 mmol L^{-1} KCl solution. Following this, 10 mL of 4 mol L^{-1} NH_4Cl were added to each sample to give a 1 mol L^{-1} NH_4Cl

solution to displace K from the exchange complex. After shaking for 30 min, soils were centrifuged, and exchanged K in the solution was measured by flame emission using an atomic absorption spectrophotometer (Perkin Elmer, Norwalk, CT). Standards were prepared in 1 mol L^{-1} NH_4Cl solution to match the matrix of the soil extracts. The amount of K^+ not displaced by NH_4^+ was considered to be fixed and was calculated as the difference between the initial K added and the extracted K. Therefore, a positive Kfix value indicates fixation while negative values indicate release of K. The base saturation of K (Ksat) and cation exchange capacity (CEC—Rhoades 1982) were analyzed at a commercial laboratory (Midwest Laboratories—midwestlabs.com). Soil mineralogical analysis was done on eight soils with a range in Kfix potential to better ascertain soil mineralogical properties associated with K fixation. This was done by removing carbonates and organic matter, and dispersing the soil to separate sand, silt, and clay fractions as described by Jackson (1975). The mineral composition of the clay (< 2 µm) and silt (2–50 µm) fractions was determined by X-ray diffraction following methods of Whittig and Allardice (1986).

Plant sampling and analysis

Flag-leaf samples were taken between flag-leaf formation (R2) and anthesis (R4) (Counce et al. 2000) from the same basins the soil samples were taken. Within the same basin being sampled it was not unusual to sample flag leaves that were at both R2 and R4. At least 30 flag-leaf samples were taken by walking across each basin and randomly sampling leaves. Flag-leaf samples were pooled for each basin, put in an oven drier (60 °C) and ground for analysis in a ball mill grinder. The ground leaf tissue was analyzed for K at the UC Davis Analytical Lab (Jones 2001; U.S. EPA 2001).

Irrigation water sampling and analysis

Irrigation water was sampled two times during the season (in June and July) at the inlet of each field. Water was collected in an acid washed dark 1 L bottle. To sample, irrigation water was collected in the bottle three times to rinse before collecting the final sample. Bottles were immediately stored on ice in a cooler until they were placed in a cold room to await analysis. Soluble potassium was analyzed by the UC Davis Analytical Lab using ICP-AES.

Soil K balance

Field K balances were calculated based on grower practices for that field, accounting for K fertilization, K concentration of irrigation water, winter flooding practices and straw management. The annual field K balance was calculated using the following formula:

$$\begin{aligned}\text{Annual field K balance} = &\text{Fertilizer K} + \text{K balance in irrigation water during growing season} \\ &- \text{K removed at harvest} - \text{K balance in irrigation water during winter fallow season}\end{aligned}$$

Data on K fertilizer inputs, yield (14% moisture), and straw and winter flood management were collected from growers for the 5-year period before the study year. Nine fields did not have the necessary data to calculate a balance (Table 1). For K removal in harvested grain, we assumed a grain K concentration of 0.25% K (Dobermann and Fairhurst 2000). Growers were asked how many years straw was removed from the field following harvest. To calculate straw K removal, we assumed a harvest index of 0.50, that 50% of the straw in the field was removed, and a straw K concentration of 1.39% (Dobermann and Fairhurst 2000). When rice straw was burned following harvest, it was assumed that the straw K remained in the field (Paul and Negi 2008).

During the growing season, accounting for irrigation water coming into and leaving the field in tailwater, Linquist et al. (2014) reported that irrigation water K added, on average by 4.9 kg K ha^{-1}, to the system. This is similar to findings by Krupa et al. (2011). The Linquist et al. (2014) study included fields that used irrigation water from the Sacramento and Sierra rivers (Feather, Yuba, Bear and American Rivers). For the purpose of estimating K budgets in this study, irrigation water K concentration was measured during

Table 1 Soil order, irrigation source, and management practices important for estimating K budget at each site. Site number refers to sites shown in Fig. 1

Site	Soil Order	Irrigation source	K fertilizer added in study year	Average annual K application	Years straw baled in last 5 years	Years winter flooded in last 5 years	Average annual removal of K in grain/straw	Soil K balance
			(Yes/No)	kg K ha^{-1} yr^{-1}			kg K ha^{-1} yr^{-1}	kg K ha^{-1} yr^{-1}
1	Vertisol	Sacramento	No	0	0	1	23.0	−20
2	Vertisol	Sacramento	No	0	0	1	23.0	−20
3	Vertisol	Sacramento	No	0	2	5	23.8	−33
4	Vertisol	Sacramento	No	0	0	0	50.3	−45
5	Vertisol	Sacramento	No	0	0	0	23.8	−18
6	Vertisol	Sierra	Yes	20	0	5	24.6	−16
7	Vertisol	Sierra	Yes	20	0	5	24.6	−16
8	Vertisol	Sierra	Yes	20	0	5	–	−17
9	Alfisol	Sierra	Yes	48	na	na	27.5	na
10	Alfisol	Sierra	Yes	48	na	na	21.7	na
11	Vertisol	Sierra	Yes	20	0	3	27.2	−12
12	Vertisol	Sierra	Yes	20	0	5	25.5	−17
13	Vertisol	Sierra	Yes	17	0	5	26.3	−20
14	Vertisol	Sierra	Yes	17	0	5	25.2	−19
15	Vertisol	Sierra	Yes	20	0	5	25.0	−16
16	Vertisol	Sacramento/ Sierra	No	0	0	0	26.3	−21
17	Alfisol	Sacramento/ Sierra	No	0	0	0	25.2	−20
18	Vertisol	Sacramento	Yes	na	1	4	36.6	na
19	Alfisol	Sacramento	No	0	0	0	22.8	−17
20	Alfisol	Sacramento	No	0	0	0	22.8	−17
21	Alfisol	Sacramento	No	0	0	1	22.8	−20
22	Alfisol	Sacramento	No	0	0	1	22.8	−20
23	Vertisol	Sierra	Yes	33	0	5	27.2	−5
24	Mollisol	Sacramento	No	0	0	0	25.8	−20
25	Mollisol	Sacramento	No	0	0	0	25.8	−20
26	Vertisol	Sacramento	No	0	0	0	26.6	−21
27	Vertisol	Sierra	Yes	84	0	5	26.3	47
28	Alfisol	Sierra	Yes	57	0	5	24.5	21
29	Mollisol	Sacramento	No	32	0	5	25.2	−3
30	Entisol	Sierra	Yes	na	na	na	na	na
31	Vertisol	Sacramento/ Sierra	No	0	0	1	24.6	−23
32	Alfisol	Sierra	No	0	0	0	21.8	−18
33	Mollisol	na	No	22	0	0	20.9	6
34	Histosol	Sacramento/ Sierra	Yes	52	0	5	23.8	18
35	Vertisol	Sacramento	Yes	20	0	5	26.3	−16
36	Vertisol	Sierra	Yes	23	0	5	25.2	−13
37	Alfisol	Well	Yes	19	0	0	24.6	8
38	Vertisol	Sacramento	No	4	0	0	24.5	−15

Table 1 (continued)

Site	Soil Order	Irrigation source	K fertilizer added in study year (Yes/No)	Average annual K application kg K ha^{-1} yr^{-1}	Years straw baled in last 5 years	Years winter flooded in last 5 years	Average annual removal of K in grain/straw kg K ha^{-1} yr^{-1}	Soil K balance kg K ha^{-1} yr^{-1}
39	Vertisol	Sacramento	No	0	na	5	96.5	na
40	Alfisol	Well	No	0	0	0	18.8	−11
41	Alfisol	Well	No	0	0	0	19.9	−13
42	Alfisol	Well	No	na	0	0	23.8	na
43	Vertisol	Sierra	No	0	0	5	23.5	−34
44	Vertisol	Sierra	No	0	0	5	23.4	−34
45	Alfisol	Sierra	No	0	0	0	20.5	−16
46	Alfisol	Sierra/Well	Yes	67	0	5	24.6	28
47	Alfisol	Sacramento	No	0	0	0	21.0	−15
48	Alfisol	Sacramento	No	0	0	5	26.0	−35
49	Alfisol	Sacramento	No	0	0	5	24.9	−34
50	Alfisol	Sacramento	No	0	4	0	77.6	−72
51	Inceptisol	Slough	Yes	56	0	5	25.8	19
52	Vertisol	Sierra	No	0	0	5	25.8	−37
53	Alfisol	Sierra	No	0	0	na	24.4	na
54	Entisol	Well	No	0	0	na	23.8	na
55	Vertisol	Sierra	No	0	0	na	24.9	na

na=not available

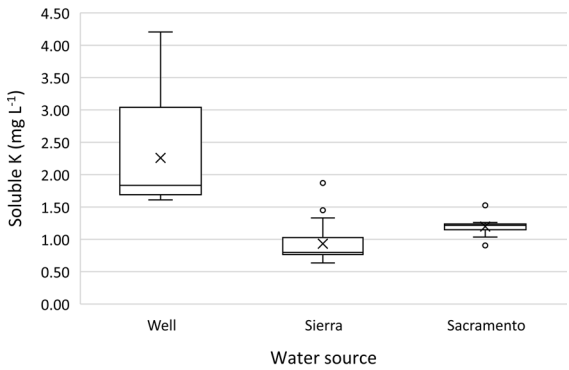


Fig. 2 Soluble K concertation in irrigation water for the experimental sites depending on irrigation water source. The K concentration is the average of the two sampling events. The median is the line through the box and the average is marked by an "X". The upper and lower quartiles represent 75% and 25%, respectively. Outliers are marked by open circles. Well (n = 5) is irrigation water from a well. Sierra (n = 24) is all irrigation water from all rivers originating in the Sierra Nevada mountain range (includes Feather, Yuba, Bear and American Rivers). Sacramento (n = 20) is irrigation from the Sacramento River. If the irrigation source was not known or if several sources were blended, the data were not included (n = 6)

the study season at two times and was assumed to be reflective of the previous 5 years. Irrigation water K concentrations were higher in the Sacramento River than rivers originating in the Sierra Nevada mountain range (Fig. 2). For the growing season, the average input of K from irrigation water (Linquist et al. 2014) was adjusted for the different K concentrations of the irrigation source. Thus, fields receiving Sacramento and Sierra river waters added 5.7 and 4.1 kg K ha^{-1}, respectively, which represents the average relative difference between these two water sources. In wells, the K concentration was higher and more variable, thus the K input from due to irrigation well water was adjusted individually by field. For the winter fallow season, Linquist et al. (2014) reported that if fields were flooded (which also resulted in tailwater flows), on average, 15 kg K ha^{-1} was removed from the system. Thus, we used this value, if fields were flooded during the winter. All fields flooded during the winter received either Sacramento or Sierra river water (i.e., no fields were winter flooded with well water).

Data analysis

The relationship between K balance and soil properties was done at the field scale; therefore, soil K values from the individual basins from a given field were averaged for the analysis. Regression and Pearson Correlation Analysis (Statistix 10.0 2017) were used to examine relationships between soil properties and K fertility indices (plant and soil). Results were considered significant when $P < 0.01$. When examining the specific relationship between soil K properties (Kext, Ksat, Kfix, and Ca + Mg:K ratio) and plant K deficiency symptoms (flag-leaf K-dependent variable), only fields that did not receive K fertilizer in the study year (year that the soil samples were collected; 34 fields; 100 soil and flag-leaf samples) were used for the analysis. We reasoned that application of K fertilizer during the sampling year would mask the relationship between soil K and plant K. A crop was considered K deficient when the flag-leaf K concentration was less than 1.2% (Dobermann and Fairhurst 2000).

Results

Soils and irrigation water

Field sites were well distributed around the rice-growing region of California (Fig. 1). The dominant soil order (based on soil map units) represented in this study was Vertisols, followed by Alfisols (Table 1). The soil properties in Table 2 represent the means of up to three samples taken from each field. Total organic carbon (TOC) ranged from 0.70 to 7.71%. The soil (#34) with a TOC of 7.71 was a Histosol. Soil CEC ranged from 7.6 to 53.1 cmol(+) kg^{-1}. Soil pH ranged from 4.6 to 7.0. Clay content ranged from 11 to 57%. For the various K indices, soil Kext ranged from 42 to 285 mg K kg^{-1} (mean = 147 mg K kg^{-1}), Ksat ranged from 0.7 to 3.2% (mean = 1.7%), the (Ca + Mg):K ratio ranged from 8 to 61 (mean = 21) and Kfix ranged from + 223 to − 453 mg K kg^{-1}.

The variability of the soil properties across a field (in fields where more than one sample was taken) was relatively consistent with respect to clay content, CEC and pH, where the coefficient of variation (CV) was less than 8%. In contrast, the variability in the soil K indices was higher. For example, the CV of Kext averaged 15%. A closer examination of this variability indicates that the Kext in the bottom basin (irrigation water flowing from top to bottom basins) was, on average, 21% higher than the other basins.

The K concentration in irrigation water varied depending on water source. On average, well water had the highest K concentration (2.3 mg K L^{-1}) and the greatest variability in K concentration (Fig. 2). Irrigation water originating from the Sacramento River had an average K concentration of 1.3 mg K L^{-1}, while irrigation water originating from Sierra Nevada rivers had the lowest concentration (0.9 mg K L^{-1}).

Soil K balances

Soil K balances were quantified for 46 fields of the 55 fields in the study as a complete data set was not available for nine fields (Table 1). Of the remaining 46 fields, 19 received fertilizer K in at least one of the preceding 5 years. The average annual K fertilizer application rate (averaged over the 5 years before the study period) for fields receiving K fertilizer was 29 kg K ha^{-1} (range 4–84 kg K ha^{-1}). The K balance averaged − 15 kg K ha^{-1} yr^{-1} and ranged from − 72 to 47 kg K ha^{-1} yr^{-1}. Only two of the fields (#3 and 50) had any history of straw baling and these fields had a K balance of − 33 and − 72 kg K ha^{-1} yr^{-1}, respectively.

There was no relationship between Kext and K balance (Fig. 3). Of the seven fields with positive K balance, four had Kext values that were below 120 mg K kg^{-1} and none of these were on K fixing soils.

Relationship between soil properties and soil K indices

Examining the relationship between soil properties and various K indices, Kext was positively correlated with TOC (0.35), CEC (0.34) and clay content (0.46) (Table 3). Both Ksat and Kfix were negatively correlated with TOC (− 0.23 and − 0.24, respectively) and clay content (− 0.43 and − 0.23, respectively); but positively correlated with pH (0.30 and 0.22, respectively). Ksat was also negatively correlated with CEC (− 0.55). With respect to the relationships among the soil K indices, Kext was positively correlated with Ksat (0.40) and negatively with Kfix (− 0.59) and the

Table 2 Average (standard deviation) flag-leaf K concentration and soil properties including extractable K (Kext), percent K saturation (Ksat) and the K fixation potential (Kfix) for each field. Means and standard deviation represent the field average of samples taken from each basin in the field.

Field	Flag-leaf K (%)	Clay (%)	Total organic C (%)	CEC (meq 100 g^{-1})	pH	Kext (mg kg^{-1})	Ksat (%)	Kfix (mg kg^{-1})	(Ca + Mg):K ratio
1	1.73 (0.1)	40 (3.5)	1.89 (0.2)	25.0 (4.7)	4.9 (0.1)	242 (47)	2.1 (0.3)	− 339 (22)	10.7 (1.7)
2	1.82 (0.2)	39 (2.1)	1.74 (0.1)	23.5 (4.4)	5.2 (0.2)	186 (23)	1.9 (0.3)	− 268 (42)	13.9 (1.4)
3	1.68 (0.0)	57 (5.0)	2.03 (0.5)	40.9 (0.4)	5.9 (1.0)	285 (78)	1.9 (0.5)	− 385 (166)	17.6 (2.5)
4	1.60 (0.1)	39 (2.5)	1.82 (0.1)	26.9 (0.7)	6.5 (0.6)	134 (15)	1.6 (0.1)	− 173 (50)	23.1 (2.2)
5	1.58 (0.1)	27 (2.5)	1.59 (0.0)	25.4 (1.5)	5.7 (0.3)	143 (35)	1.6 (0.3)	− 149 (64)	20.6 (4.5)
6	1.46 (0.1)	40 (1.2)	2.00 (0.2)	37.8 (1.7)	4.9 (0.1)	196 (17)	1.4 (0.1)	− 344 (62)	15.6 (2.5)
7	1.45 (0.1)	41 (1.0)	1.66 (0.2)	35.6 (0.5)	4.8 (0.1)	198 (8)	1.4 (0.1)	− 453 (11)	15.1 (0.6)
8	1.56 (0.1)	48 (1.5)	1.77 (0.0)	41.6 (0.9)	4.8 (0.0)	222 (66)	1.4 (0.4)	− 448 (63)	15.2 (4.6)
9	1.56 (0.1)	16 (2.6)	1.01 (0.1)	9.1 (1.7)	5.4 (0.4)	72 (24)	2.2 (0.4)	− 202 (64)	15.0 (3.1)
10	1.93 (0.2)	15 (3.2)	1.32 (0.2)	8.2 (1.4)	5.4 (0.2)	105 (14)	2.9 (0.3)	− 176 (67)	10.7 (1.5)
11	1.37 (0.1)	52 (1.2)	1.70 (0.3)	42.4 (0.3)	4.8 (0.2)	150 (18)	1.0 (0.1)	− 203 (35)	25.5 (4.7)
12	1.39 (0.0)	55 (4.6)	1.98 (0.2)	51.3 (1.2)	5.3 (0.1)	110 (20)	0.7 (0.1)	− 156 (97)	52.6 (8.7)
13	1.54 (0.1)	41 (2.1)	2.35 (0.3)	32.1 (5.9)	4.6 (0.0)	105 (26)	0.7 (0.3)	− 44 (72)	31.9 (13.0)
14	1.72 (0.1)	39 (2.0)	2.44 (0.0)	31.0 (2.7)	4.8 (0.2)	121 (15)	1.0 (0.1)	− 97 (47)	24.5 (1.0)
15	1.35 (0.1)	57 (1.2)	2.17 (0.5)	53.1 (3.3)	5.7 (0.2)	127 (20)	0.9 (0.1)	+ 37 (13)	42.2 (4.3)
16	1.35 (0.2)	33 (3.2)	2.09 (0.5)	25.5 (3.1)	5.2 (0.1)	89 (22)	1.0 (0.1)	+ 60 (58)	32.5 (6.1)
17	1.50 (0.0)	35 (0.6)	1.39 (0.2)	27.4 (1.9)	4.7 (0.0)	131 (25)	1.2 (0.2)	− 38 (27)	20.3 (2.2)
18	1.61 (0.1)	27 (2.5)	1.87 (0.1)	20.4 (1.9)	5.3 (0.2)	163 (25)	1.9 (0.3)	− 65 (74)	15.6 (2.1)
19	1.55 (0.1)	29 (2.6)	0.99 (0.1)	18.9 (2.2)	5.5 (0.1)	232 (23)	3.2 (0.1)	− 229 (18)	11.0 (0.5)
20	1.52 (0.0)	29 (1.2)	0.90 (0.1)	17.6 (0.1)	5.4 (0.1)	224 (17)	3.2 (0.3)	− 234 (22)	10.6 (0.9)
21	1.52 (0.0)	31 (1.5)	1.02 (0.1)	18.6 (0.7)	5.5 (0.1)	228 (15)	3.1 (0.2)	− 267 (46)	10.7 (1.1)
22	1.51 (0.0)	42 (2.0)	1.12 (0.2)	26.6 (2.6)	5.6 (0.2)	266 (43)	2.7 (0.4)	− 309 (126)	13.1 (2.8)
23	1.57 (0.0)	57 (3.8)	1.66 (0.2)	49.3 (2.2)	5.3 (0.2)	162 (21)	1.1 (0.1)	− 145 (24)	30.5 (3.3)
24	1.66 (0.1)	34 (6.9)	1.67 (0.2)	24.8 (4.3)	6.0 (0.2)	155 (47)	1.7 (0.1)	− 22 (120)	21.8 (2.4)
25	1.67 (0.0)	32 (7.5)	1.54 (0.2)	23.2 (3.3)	6.2 (0.1)	144 (41)	1.6 (0.2)	− 5 (56)	23.4 (2.4)
26	1.59 (0.0)	56 (4.0)	1.89 (0.2)	36.8 (1.3)	6.3 (0.1)	189 (20)	1.5 (0.2)	+ 27 (12)	25.0 (3.4)
27	1.48 (0.1)	46 (2.3)	1.93 (0.1)	36.2 (2.6)	4.8 (0.0)	96 (12)	0.8 (0.0)	− 96 (17)	33.4 (1.7)
28	1.63 (0.2)	17 (1.0)	1.26 (0.2)	11.6 (1.4)	4.7 (0.1)	56 (17)	1.2 (0.2)	− 40 (36)	17.1 (2.8)
29	1.58 (0.1)	36 (3.5)	2.10 (0.1)	23.1 (3.6)	6.4 (0.1)	183 (8)	2.1 (0.2)	− 129 (49)	17.2 (1.5)
30	1.62 (0.1)	11 (3.8)	0.70 (0.1)	8.0 (0.9)	5.4 (0.2)	42 (7)	1.4 (0.2)	− 34 (8)	21.8 (1.9)
31	1.54 (0.1)	39 (.06)	1.84 (0.1)	30.7 (1.6)	5.1 (0.2)	129 5()	1.2 (0.1)	− 167 (88)	22.9 (0.2)
32	1.43 (0.2)	15 (2.1)	1.05 (0.2)	7.6 (2.7)	4.8 (0.0)	63 (17)	2.5 (0.8)	− 57 (24)	10.2 (2.6)
33	1.41 (0.1)	40 (6.8)	1.59 (0.2)	29.2 (2.5)	5.1 (0.2)	135 (12)	1.4 (0.1)	− 142 (55)	23.5 (2.4)
34	1.47 (0.0)	35 (1.5)	7.71 (0.6)	26.0 (1.8)	5.9 (0.1)	276 (29)	1.5 (0.2)	− 388 (82)	23.4 (3.1)
35	1.34 (0.0)	44 (1.2)	2.39 (0.2)	27.4 (1.0)	5.8 (0.0)	212 (54)	1.8 (0.5)	− 225 (53)	19.4.20
36	1.38 (0.1)	37 (5.1)	2.12 (0.2)	30.4 (4.8)	5.5 (0.1)	167 (25)	1.7 (0.2)	− 139 (55)	20.3 1.9()
37	1.34 (0.1)	23 (4.2)	1.35 (0.1)	16.5 (2.7)	6.9 (0.1)	147 (11)	2.4 (0.3)	− 28 (75)	16.7 (1.3)
38	1.30 (0.1)	40 (1.0)	1.66 (0.2)	29.2 (1.0)	5.2 (0.3)	200 (10)	1.8 (0.1)	− 197 (85)	17.4 (1.8)
39	1.33 (0.0)	42 (0.0)	2.09 (0.1)	29.3 (1.6)	5.4 (0.1)	178 (7)	1.7 (0.1)	− 228 (19)	17.6 (1.1)
40	1.27 (0.0)	22 (2.0)	1.23 (0.1)	14.4 (1.4)	5.9 (0.0)	66 (10)	1.4 (0.1)	+ 168 (30)	25.5 (1.0)
41	1.19 (0.3)	18 (0.0)	1.11 (0.1)	10.2 (0.4)	5.7 (0.2)	53 (12)	1.5 (0.3)	+ 223 (10)	24.3 (4.4)
42	1.50 (0.2)	20 (1.7)	1.16 (0.0)	12.7 (1.2)	5.6 (0.2)	116 (13)	2.6 (0.0)	+ 83 (80)	14.0 (0.9)

Table 2 (continued)

Field	Flag-leaf K (%)	Clay (%)	Total organic C (%)	CEC (meq 100 g^{-1})	pH	Kext (mg kg^{-1})	Ksat (%)	Kfix (mg kg^{-1})	(Ca + Mg):K ratio
43	1.21 (0.1)	47 (2.6)	1.74 (0.2)	33.9 (2.7)	5.3 (0.3)	107 (8)	1.0 (0.0)	+ 173 (110)	31.2 (3.1)
44	1.29 (0.0)	44 (4.0)	1.51 (0.1)	30.8 (4.0)	5.1 (0.0)	137 (5)	1.3 (0.1)	− 21 (26)	21.8 (1.3)
45	1.48 (na)	24 (na)	1.27 (na)	19.3 (na)	4.6 (na)	106 (na)	1.5 (na)	− 98 (na)	12.0 (na)
46	1.38 (0.1)	25 (1.5)	1.53 (0.2)	14.0 (2.9)	4.6 (0.0)	102 (29)	1.9 (0.4)	− 185 (55)	11.4 (2.0)
47	1.50 (0.2)	21 (2.3)	1.49 (0.2)	11.6 (0.9)	5.7 (0.5)	134 (22)	2.6 (0.1)	− 281 (64)	12.5 (1.8)
48	1.29 (0.0)	27 (2.3)	1.71 (0.2)	16.0 (1.1)	5.0 (0.0)	112 (25)	1.7 (0.3)	− 360 (163)	13.5 (2.3)
49	1.31 (0.2)	23 (2.5)	1.43 (0.1)	13.7 (0.5)	5.0 (0.0)	89 (25)	1.7 (0.3)	− 298 (42)	13.8 (2.5)
50	1.24 (0.1)	29 (4.0)	2.14 (0.1)	17.3 (2.5)	6.7 (0.3)	98 (8)	1.6 (0.1)	− 76 (68)	25.6 (1.5)
51	1.32 (na)	24 (na)	1.52 (na)	13.4 (na)	5.1 (na)	107 (na)	1.8 (na)	− 249 (na)	14.4 (na)
52	1.11 (0.1)	55 (0.6)	1.71 (0.2)	45.9 (1.7)	5.1 (0.3)	128 (23)	1.0 (0.1)	− 389 (41)	34.4 (6.3)
53	1.24 (0.1)	29 (8.9)	1.78 (0.8)	23.8 (3.9)	4.8 (0.1)	102 (45)	1.1 (0.2)	− 281 (87)	23.8 (4.7)
54	1.40 (0.1)	27 (2.1)	1.86 (0.1)	19.1 (2.9)	5.3 (0.1)	90 (6)	1.3 (0.3)	− 97 (61)	23.4 (4.1)
55	1.27 (0.0)	23 (1.0)	2.46 (0.3)	21.8 (1.3)	7.0 (0.4)	188 (22)	2.2 (0.1)	− 169 (26)	18.0 (0.6)

Two sites only had one sample location-thus standard deviation is not available (na). Site number refers to sites shown in Fig. 1

(Ca + Mg):K ratio (− 0.34). Soil Kfix was not significantly correlated with Ksat.

Relationship between mineralogy and K fixation

In the eight soils selected to analyze the relationship between clay mineralogy and K fixation, the Kfix ranged from + 242 to − 460 mg K kg^{-1}. Seven of the soils had relatively high clay content (31–58%), while one had a clay content of 18% (Table 4). Smectite and kaolinite were the dominant minerals in the clay fraction; while quartz was the dominant mineral in the silt fraction. Vermiculite was present in all soils, but was not a dominant mineral in any of them (estimated to be 6–12% of the clay fraction based on X-ray diffraction peak intensities). There was no clear relationship between Kfix and soil minerology.

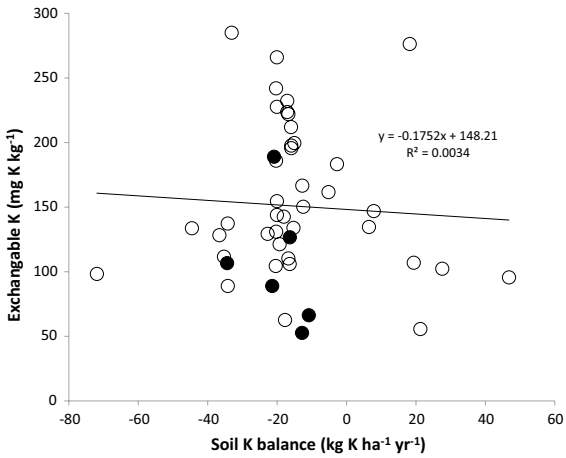


Fig. 3 The relationship between soil K balance (based on input–output budget over 5 years previous to study) and exchangeable soil K. The solid circles represent K fixing soils

Geographical distribution

Geographically all fields were located in the Sacramento Valley, except for three which were located further south (Stockton area—Fig. 1). Soils with low Kext (< 120 mg kg^{-1}) and Ksat (< 1.6%), and K fixing soils were primarily found on the east side of the valley. Only one K fixing field and three fields low in Kext, were found on the west side of the valley. K fixing soils were most predominant in the SE portion of the valley, while low Kext soils were common along the eastern rim of the valley.

Soil K versus flag-leaf K

When determining the relationship between soil K and flag-leaf K concentrations, only fields that did not receive K fertilizer in the study year were

Table 3 Mean, range and Pearson correlation analysis of total organic carbon (TOC), clay, pH, cation exchange capacity (CEC), exchangeable K (Kext), K saturation (Ksat) and the K fixation potential (Kfix) of all soil samples in the study (n = 160)

	Range	Mean	units	TOC	clay	pH	CEC	Kext	Ksat	Kfix	CaMg:K
TOC	0.58–8.29	1.77	%	1.00	0.25	ns	0.25	0.35	−0.23	−0.24	ns
Clay	8–62	35	%		1.00	ns	0.94	0.46	−0.43	−0.23	0.49
pH	4.6–7.4	5.4	–			1.00	ns	ns	0.30	0.22	ns
CEC	5.9–56.7	25.6	meq 100 g^{-1}				1.00	0.34	−0.55	ns	0.61
Kext	35–349	147	mg kg^{-1}					1.00	0.40	−0.59	−0.34
Ksat	0.9–3.5	1.7	%						1.00	ns	−0.75
Kfix	242 to −538	−152	mg kg^{-1}							1.00	0.36
CaMg:K	8.2–60.7	20.6	–								1.00

Only significant correlation coefficients ($P < 0.01$) are shown

Table 4 Mineralogy of clay and silt fractions based on X-ray diffraction peaks from eight soils with varying K fixation (Kfix) capacity. Sites are ordered based on Kfix. The more positive the Kfix, the greater the K fixation potential. Site ID refers to sites in Table 1 and Fig. 1. A positive Kfix indicates K fixation potential

Site ID	Clay mineralogy[a] (< 2 µm)	Silt mineralogy[a] (2–50 µm)	Kfix Mg kg^{-1}	Sand	Silt %	Clay
43	S,K,V,Q,F,M[b]	Q,F,H,K,V	242	16	35	49
41	K,Q,S,F,V,M	Q,F,H,M,K	224	45	37	18
15	S,K,F,V,Q,M	Q,F,H,C,K	52	23	21	56
26	S,Q,K,M,C,V,F	Q,K,F,C,V,S,M,H	29	13	29	58
19	S,Q,K,M,V,F	Q, F,K,S,V,M	−243	41	28	31
31	S,K,Q,M,V,F,C	Q,F,H,K,V,S,C	−256	31	29	40
1	K,Q,S,V,M,F	Q,F,K	−353	20	42	38
7	S,K,Q,M,V,F	Q,F,K	−460	24	36	40

[a]Minerals are listed in order of decreasing peak area, most intense listed first

[b]Abbreviations: C, Chlorite; F, Feldspar; H, Hornblende; K, Kaolinite; M, Mica; Q, Quartz; S, Smectite; V, Vermiculite

Table 5 Pearson correlation analysis of leaf K concentration (LeafK) versus the following soil properties: exchangeable K (Kext), K saturation (Ksat) and the K fixation potential (Kfix), clay, pH, cation exchange capacity (CEC), total organic carbon (TOC)

	LeafK	*P* value
Kex	0.4788	0.0000
Ksat	0.3530	0.0003
Kfix	−0.1936	0.0536
(Ca + Mg):K ratio	−0.4278	0.0000
Clay	0.1518	0.1317
pH	0.1164	0.2486
CEC	0.0443	0.6618
TOC	0.0087	0.9316

Sites were only included in this analysis if they did not receive fertilizer K at the onset of the growing season (n = 100)

included (34 of 55 fields—total of 100 samples) in order to remove the effect of fertilizer K. Soil Kext ranged from 42 to 349 mg K kg^{-1} (mean 150 mg K kg^{-1}) and the flag-leaf K concentrations ranged from 0.98 to 2.01%. Kext was the most correlated with flag-leaf K concentration, followed by the (Ca + Mg):K ratio and Ksat (Table 5). Soil Kfix ($P = 0.054$), clay, pH, CEC, TOC were poorly or not significantly correlated with flag-leaf K. As with the Pearson correlation analysis (Table 5), Kext ($r^2 = 0.26$) was more closely correlated with flag-leaf K than Ksat ($r^2 = 0.21$), but both relationships were poor.

Discussion

Soil K balance versus soil K and plant K availability indices

This study represents a broad and representative set of fields, soils, and management practices from the California rice-growing region. The most common soil order represented were Vertisols (49%); the same as a similar study conducted in the same region on phosphorus (Linquist et al. 2011). Whether or not a farmer applied K fertilizer was not a criterion for site selection, and 36% of rice farmers in the study applied K fertilizer. For those applying fertilizer, the average fertilizer rate was 29 kg K ha^{-1} (range 4–84 kg K ha^{-1}). These results are similar to a survey that was conducted in 2003 with California rice farmers, where it was reported that 39% of the farmers applied K fertilizer at an average rate of 40 kg K ha^{-1} (Hartley and van Kessel 2003). Williams (2010) also reported that average K rates for California farmers applying K fertilizer was 28 kg K ha^{-1}. In the 5 years leading up to the study year (the years the K balance was based on), yields averaged 9.71 Mt ha^{-1} (range 7.50–10.99 Mt ha^{-1}); similar to statewide yield averages for rice during this period (USDA 2021).

Straw management was not considered when selecting fields. In most fields (95%), farmers did not remove straw from the field following harvest (removed from 3 fields in at least one of the 5 years prior to this study—Table 1). The majority incorporated the straw and flooded the field to aid in rice straw decomposition (Linquist et al. 2006), although in some cases rice straw was burned. Rice straw was burned in 20% of the fields in at least one of the 5 years prior to the study. Rice straw burning retains most of the straw K in the field (Paul and Negi 2008).

On average, soil K balances were negative and averaged − 14.9 kg K ha^{-1} yr^{-1}. In only seven fields, were K balances positive (Fig. 3). The removal of K due to grain harvest averaged 24 kg K ha^{-1} in this study. While the average K rate of 29 kg K/ha exceeded the average rate of K removal, 55% of growers who applied K used an annual rate of only 13–19 kg K/ha, which would have still resulted in a negative K balance on the basis of grain K removal alone.

The negative K balances suggest that over time K deficiencies may increase, especially for growers that do not apply K fertilizer. In a survey conducted in 1969, Mikkelsen and Hunziker (1971) identified less than 1% of the 400 rice leaf samples collected as being K deficient. In our study, 7% of the 160 flag-leaf samples indicated K deficiency (flag-leaf K concentration < 1.2%). This increase in frequency of indicators of K deficiency is consistent with a decline in soil K status over the 45 year-period between these studies, and may suggest a need for greater attention to K management strategies in these cropping systems.

Straw removal is associated with high K removal from soil because approximately 80–85% of the plant K at harvest is in the straw (Dobermann and Fairhurst 2000). Removal of rice straw is also associated with increasing K deficiency if K soil balances are not maintained (Dobermann et al. 1996a; Yadvinder-Sing et al. 2004). Unfortunately, fields in which straw was removed were poorly represented in this study. Straw was removed from only two fields during the 5-year period in question. In those two fields, straw was removed in two and four of the 5 years and the soil K balances were − 33 and − 72 kg K ha^{-1} yr^{-1}, respectively (Kext: 285 and 98 mg K kg^{-1}, respectively). Historically there has been little demand for rice straw in California. Straw was burned until restrictions were put in place in the 1990s; and since then most of the straw has been disposed of by incorporating it into the soil during the winter fallow period for decomposition (Linquist et al. 2006). In recent years, the demand for rice straw has increased for livestock feed (especially during drought years). Where straw is removed, maintenance of soil K to ensure crop productivity will be essential, as without K fertilizer additions, K deficiencies will likely become much more prominent.

Interestingly, K balances were not associated with soil K availability (Kext). In fact, four of the soils with a positive K balance had Kext values of < 120 mg kg^{-1} (Fig. 3). The lack of an increase in soil K with positive K balances has been reported on by others (Dobberman et al. 1996a; Franzen et al. 2021). The cause of this is not clear but the soils with both low Kext and positive K balance represented a broad range of clay contents and CEC (Tables 1 and 2). Furthermore, soil K balance was not associated with K-fixation (Fig. 3) or soils with high Ca + Mg:K ratios. Several possibilities exist. First, it is possible that due to winter flooding, more K is lost than we

estimated in our budget calculations. Potassium is easily washed out of straw upon flooding or rainfall (Jenkins et al. 1996; Bakker and Jenkins 2003) and K loss from the field during the winter is positively correlated with the flux of water moving through the field (Linquist et al. 2014). In the K balance equation, we used an average value for K loss due to winter flooding (15 kg K ha^{-1}); however, values of 30 to 100 kg K ha^{-1} were reported being lost in some fields with high water flow rates during the winter fallow period (Linquist et al. 2014). All four fields that had a positive K balance, but low Kext, were flooded during the winter, however we do not know how much water flowed through the fields during the winter. Second, it could be argued that developing the K budget using K inputs and outputs in incoming or outgoing water, resulted in too many assumptions and may have introduced error. Using a simplified budget (inputs from fertilizer; outputs from K removed in straw and grain) resulted in similar findings, where on average, the K balance was − 12.5 kg K ha^{-1} yr^{-1}, 10 fields had a positive K balance and no relationship between K balance and Kext (data not shown). Third, we only examined soils in the top 150 mm (plow-layer) using a similar approach to Dobermann et al. (1996a). However, Hinsinger et al. (2021) point out that K uptake from subsoil layers is often overlooked. While the plow layer is where most of the roots are located in rice systems, rice roots do extend deeper (e.g. Carrijo et al. 2018 reported 11% of the roots below 150 mm). Thus, at least a portion of the K being taken up by rice comes from these deeper soil layers. Finally, Franzen et al. (2021), in a review of the literature across crops, reported that a mass-balance relationship is rarely achieved from the measurement of exchangeable K because of the potential for buffering of K removal from non-exchangeable K in minerals (which also vary across soils in this study) and that surplus K additions can be fixed in interlayer positions in secondary layer silicates, or sequestered in sparingly soluble neoformed secondary minerals, neither of which are measured as exchangeable.

Importantly, these data and those from others (Dobermann et al. 1996a), suggest that given the potential for K loss and fixation, it is not a good management strategy to try to "build-up" soil K by applying a lot of K in 1 year; instead, annual applications of the amount needed may be a better approach. This is in contrast to phosphorus, where Linquist and Ruark (2011) found that P could be built up on these rice soils because the potential for loss was low.

Soil K fixation versus soil K and plant K availability indices

Soils that fixed K were not prominent in this study as only 25 of the 160 soil samples fixed K. When samples were averaged for each field, only seven of the 55 fields were K fixing (Table 2). Furthermore, the K fixation potential was generally low. Of the K fixing soils, the average Kfix was 101 mg K kg^{-1} (range 3–242 mg K kg^{-1}). Only five soil samples had Kfix values > 200 mg K kg^{-1} and these samples were from two fields (#41 and 43 – Table 2). In other California studies, Kfix values up to 384 mg K kg^{-1} have been reported in the soil surface (Murashkina et al. 2007a). Kfix was negatively correlated with soil Kext (Table 3) and Kext was always less than 200 mg K kg^{-1} in K fixing soils. However, K fixation was only weakly correlated ($P = 0.053$) with flag-leaf K (Table 2) and was not related to soil K balances (Fig. 3).

Five of the seven K-fixing fields were in the southeastern portion of the Sacramento Valley (Fig. 1). The other two were in the southwestern (site #26) and northeastern (site #15) portion of the valley. These findings support those of others who have reported a greater prevalence of K-fixing soils on the eastern side of the San Joaquin Valley relative to the western side (Murashkina et al. 2007a, b). The Sacramento Valley lies just north of the San Joaquin Valley. The Sacramento Valley is bordered on the east by the Sierra Nevada and Cascade Ranges and on the west by the Coast Range. Coast Range-derived soils generally have high Kext and little or no K-fixation, while the Sierra Nevada-derived soils that contain granitic alluvium generally fix K (Murashkina et al. 2007a). Others (Murashkina et al. 2007b; Pettygrove et al. 2011) reported that in the San Joaquin Valley, K-fixation was largely due to the presence of vermiculite, a weathering product of biotite, and a common constituent of the granitic rock of the Sierra Nevada. This is also supported by Sparks (1987) who reported that K-fixation is mostly due to vermiculite, although others have reported that weathered micas and high-charge smectites also fix K (Bell et al. 2021a). The Feather, Yuba and Bear River watersheds along the eastern side of the Sacramento Valley contain a

significant amount of granitic rock (geologic maps of the Chico and Sacramento 1:250,000 quadrangles); although the lithology of the northern Sierra Nevada and southern Cascade Range (which boarders the Sacramento Valley) is much less dominated by granitic rock than is the southern Sierra Nevada that borders the San Joaquin Valley. In contrast, the Coast Range consists of marine sedimentary and metamorphosed sedimentary rock at the latitude of interest (geologic map of the Ukiah 1:250,000 quadrangle), so it contributes little vermiculite to westside soils. Soils in the most northern portion of the Sacramento Valley are derived from alluvium from the Cascades, northern Coast Range and Klamath Mountains, with little granitic rock and few sources of vermiculite.

Eight of the soils from the study with a wide range of K fixation capacity were analyzed for their mineralogy to determine if their mineralogy would shed some light into the causes of K fixation. We anticipated that K-fixation would be related to vermiculite content, but that was not the case. Vermiculite was present in all soils, but was not a dominant mineral in any of them, regardless of their capacity to fix K (Table 4). Furthermore, vermiculite was present almost exclusively in the clay fraction, with little or none in the silt fraction; contrary to what Murashkina et al., (2007b) reported further south in the San Joaquin Valley, where they found that vermiculite was dominant in the silt and very fine sand fraction and that the vermiculite in those fractions was the main source of K-fixation. Smectite was the dominant mineral in the clay fraction for both K fixing and non-fixing soils (Table 4). Bell et al. (2021a) reported that high-charge smectites can fix Murashkina et al. (2008) concluded that beidellite, a high-charge, dioctahedral, tetrahedrally-substituted smectite, contributed to K-fixation in a San Joaquin Valley Vertisol. Our mineralogical analysis did not differentiate between high and low-charge smectites, but we speculate that beidellite, possibly derived from mica or chlorite in the parent alluvium might contribute to K fixation in some of the soils. Further, Fe-bearing smectites (e.g., nontronite) might also contribute to K fixation in some of the soils (Florence et al. 2017). We did not attempt to distinguish the presence of nontronite in our samples, but it is possible that such smectites could affect K fixation, especially given the reducing conditions that commonly occur under flooded paddy conditions. Given the data and the limited number of samples analyzed here, it would be speculative to infer further on the role of mineralogy on K fixation in these soils.

Regional variation of soil K indices

It is known that certain soil types along the eastern side of the Sacramento Valley are susceptible to K deficiencies due to low CEC (Williams 2010), or to the inherently low K content of the rocks of the Cascades and northern Sierra Nevada that contribute alluvium to this rice-growing area as discussed earlier. The geographic distribution of low Kext soils is shown in Fig. 1. Of the 160 soils (Note: Fig. 1 shows average Kext for each of the 55 fields) in this study, the Kext in 60 cases was below 120 mg kg^{-1} and 54 of these were on the east side of the Sacramento Valley. In these same soils, Ksat was typically low and K fixation more common. Furthermore, rice soils on the eastern side of the valley receive irrigation water originating from the Sierra Nevada, which contains less K than on the western side of the valley, where the Sacramento River is the primary irrigation source (Fig. 2). The K concentration of irrigation water has been reported to affect soil K balances and potential for K deficiency in other studies on rice (DeDatta and Mikkelsen 1985; Dobermann et al. 1996a, 1998). Mikkelsen and Hunziker (1971) conducted a survey of rice nutrient deficiencies in the same region based on plant K concentration in 1969 and found that the locations with low flag-leaf K levels were on the eastern side of the valley.

Soil K indices as predictors of plant K availability

Flag-leaf K concentrations below 1.2% K from fields that did not receive K fertilizer in the study year provide an indication of plant K deficiency (Dobermann and Fairhurst 2000). Soil Kext was the most strongly correlated soil K test with flag-leaf K (Table 3) and a better indicator of deficiency than Ksat in these soils (Fig. 4). Soils with low Kext were associated with soils with low clay content, low CEC, low Ksat, high Ca + Mg:K ratio, and high Kfix (Table 3) as has been noted by others (e.g. Dobermann et al. 1996b; 1998; Davatagar et al. 2012). The current critical soil Kext concentration for California rice soils is 60 mg K kg^{-1} (Williams 2010). Dobermann and Fairhurst (2000) reported a critical Kext value of

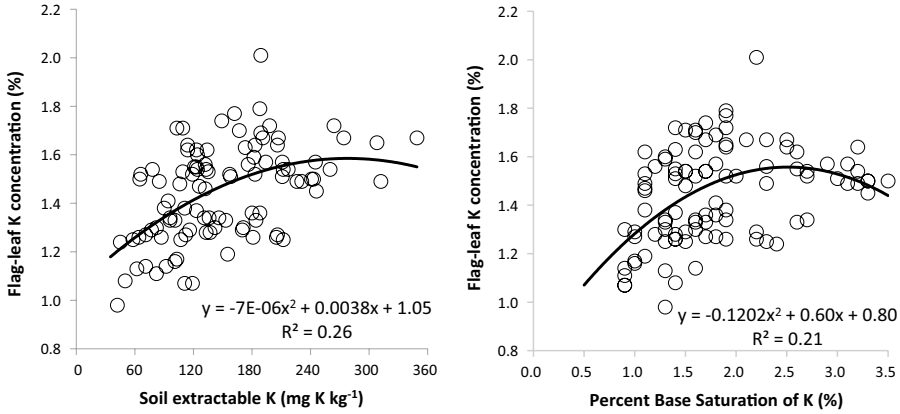


Fig. 4 Flag-leaf K concentration vs soil extractable K (left) and the percent base saturation of K (right). Only sites that did not receive K fertilizer during the study year were included in the analysis (n = 100). A flag-leaf concentration of less than 1.2% K indicates a deficiency (Dobermann and Fairhurst, 2000)

78 mg K kg^{-1}, but they also suggested that the critical value is likely higher for high yielding (> 8 t ha^{-1}) rice systems. California rice systems are among the highest yielding in the world, averaging 9.5 t ha^{-1} (USDA 2021). To determine the critical soil K levels for a K deficiency, grain yield response to increasing K concentrations is required, which was not available from this study. That said, this study does suggest that it may be important to examine critical Kext more closely to determine if a higher critical value is necessary. For example, in this study, plant K deficiencies (flag-leaf K < 1.2%) started to become apparent when Kext were below 120 mg K kg^{-1} (Fig. 4). However, the variation in flag-leaf K concentrations was large, even at very low soil K levels (< 70 mg K kg^{-1}), with values ranging from 0.98 to 1.52%. Thus, while Kext in the plow layer was not a great indicator of plant K availability, it was the best that we examined in this study. Differences in soil type (especially as related to minerology), the ability of soil tests to estimate the K pools that contribute to plant uptake, the varying potential of subsurface soil layers to provide K, and different irrigation water sources (Fig. 2) are at least part of the reason for the limitations of K indices to accurately predict K availability to plants (Bell et al. 2021b).

Conclusion

In this study, we found no correlation between K balance and soil indices related to plant available K. While soil K balances were generally negative (averaged about −15 kg K ha^{-1} yr^{-1}), Kext were generally higher than previously established critical levels. With increased straw removal and higher yields, K budgets will likely become more negative and further increase the potential for K deficiencies; however, fields where straw removal was a common practice were poorly represented in this study. Such fields would need to be specifically targeted to get a better analysis of the long-term effects of K removal. Over-fertilizing in an attempt to build up soil K may not be a good strategy because soil K balances were not related to plant available K, the potential for K losses in the system, and surplus K can be fixed. However, meeting annual K fertility requirements is a better strategy. In this study, ammonium acetate extractable K (Kext) was most closely correlated with plant K status of the indices tested. Soils that were low in ammonium acetate extractable K (Kext) were associated with soils with low clay content, low CEC, low K saturation, high CaMg:K ratio, and high K fixation. Furthermore, these low K soils were more prevalent on the eastern side of the Sacramento Valley. Importantly, in this study we did not evaluate the role of sub-plow layer soil in supply K to the plant and impacting K balance. We know a small portion of rice roots often grow into this area and this would be an interesting area for further study. Finally, as has been suggested by others, critical soil K levels need to be reassessed in situations with high crop yield potential. The current critical level for Kext in California is 60 mg K kg^{-1}. Based on our findings, this critical level should be re-evaluated, as flag-leaf K was less than 1.2% on several soils with Kext > 60 mg K kg^{-1}, indicating that the crop might benefit from K fertilization to increase Kext levels.

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