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RESEARCH ARTICLE

Potassium Fertilizer Rate Recommendations: Does Accounting for Soil Stock of Potassium Matter?

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Abstract

Profitability, yield, and fertilizer use are compared across three different potassium (K) fertilizer rate recommendation ideologies. Existing agronomic, "build and maintain" rate recommendations (KE) are compared to profit-maximizing rates with and without taking long-run soil-test K (STK) implications into account. Regardless of starting STK, K use equilibrated over the course of 3 years irrespective of ideology. Since taking long-run STK into account did not alter ending STK and only led to a miniscule yield effect, we encourage producers to use annual profit-maximizing K rates that were 3–11% lower than KE rates and generated more profit with minimal yield loss.

Keywords: Fertilizer rate recommendations; potassium; rice; soil-test K; soybean

JEL classifications: Q120; Q150; Q160

1. Introduction

An essential macronutrient in the production of agricultural commodities grown in the U.S. Mid-South region is potassium (K). Specific to both rice (*Oryza sativa* L.) and soybean (*Glycine Max* L. Merr.), K is responsible for growth, capacity to resist disease, carbohydrate translocation, photosynthesis, and enzyme reactions, all of which affect yield (Marschner, 2012). However, as agricultural demand for K fertilizer sources has increased (Dhillon et al., 2019), it is increasingly important to efficiently use this depletable resource (USGS, 2019; Zörb, Senbayram, and Peiter, 2014). Producers have the choice to apply K fertilizer at rates that (1) can "build and maintain" K as a stored resource in the soil, referred to as soil-test K (STK) from here on, or (2) are "sufficient" to attain a yield goal such as 95–100% of yield potential (Leikam, Lamond, and Mengel, 2003). The sufficiency approach requires estimation of a yield response to applied K fertilizer subject to STK. However, supplemental fertilizer use ceases when there is no longer a sufficient yield response to fertilizer (Olson et al., 1982). Risks associated with the "sufficiency" approach are the potential depletion of STK levels in a field, less than maximum yield given some crop-K deficiency, and, with potentially low STK levels, the need for supplemental K fertilizer every year even when its cost is high. In contrast, the "build and maintain" approach applies more fertilizer, despite there no longer being a yield response at higher STK levels (Leikam et al., 2003), to maintain or increase the level of STK for future crops. The argument for doing so is to provide insurance to the producer as next year's fertilizer costs could spike and to maintain or improve soil quality (Leikam et al., 2003). In past studies, the "sufficiency" approach has proven more

Table 1. Soil-test K levels as defined by Mehlich-3 extractable soil-K concentrations and corresponding agronomic fertilizer rate recommendations (K_E) for full-season irrigated rice and soybean in Arkansas

Soil-test K[a]		Fertilizer Rate Recommendations for	
		Rice	Soybean
Level	ppm	lbs K_2O/ac	lbs K_2O/ac
Very Low	<61	120	160
Low	61–90	90	120
Medium	91–130	60	60
Optimum	131–175	0	50
Above Optimum	>175	0	0

[a]Recommendations from Slaton et al. (2011) for rice and from Slaton, Roberts, and Ross et al. (2013b) for soybean represent Mehlich-3 extractable soil-K in the 0–4 inch (0–10 cm) soil layer for rice and soybean.

profitable than fertilizer strategies that build and/or maintain STK (Olson et al., 1982, Popp et al., 2020, 2021).

Current agronomic recommendations for rice as well as soybean for K fertilization aim to maintain the STK levels within the optimal or medium ranges (Table 1). These rates are considered "grower options" that aim to avoid yield losses from deficient K fertilizer use while gradually building STK in the very low and low soil test levels (Maschmann et al., 2010; Parvej et al., 2015, 2016; Slaton et al., 2009, 2010, 2011, 2013a, 2020). Also, current recommendations are mainly a function of the yield response of the crop and the STK level of a particular field. As such, these recommendations do not specifically include crop price and fertilizer cost in any given year.

Previous studies (Popp et al., 2020, 2021) have shown that K fertilizer use could be profitably curtailed when economic information is added to agronomic yield response information that is subject to STK. However, these studies did not track STK over time as most of the K-rate trial data used to estimate the yield response to K fertilizer were from multi-site, short-term field trials conducted over 20+ years that varied in soil texture as well as crop cultivars employed. Hence, there was no accounting for the value of maintaining STK in the long run.

As such, while valuable for estimating how much to curtail K fertilizer use, perhaps in a high fertilizer cost year or in a year when crop price is relatively low, using the average, multi-site yield response curves to K fertilizer that are generalizable to a variety of conditions does not value long-term effects on STK as a result of applying K at a particular rate. To that end, data from replicated long-term K-rate trials spanning 21 years were available but are limited to a particular field. In general, recommendations from a single field are less generalizable in comparison to using multiple sites, but, the data from a single-site study allow investigation of long-term effects on STK and yield as a result of plot-specific, repeated application of K fertilizer at varying rates (0–160 lbs K_2O/ac in 40-lb increments). The field was sown to a 2-year soybean-rice crop rotation that is common to the production region, making the findings generalizable from a crop rotation management perspective.

Quantifying these long-term effects on STK, which vary based on criteria and data used to make fertilizer rate recommendations, has important ramifications on nutrient runoff, risk exposure, and profitability. Importantly, we can also quantify whether short-term decisions are different from a framework where long-term effects on STK are valued.

Therefore, the objectives of this study were to examine how current fertilizer rate recommendations based on agronomic information and a "build and maintain" philosophy utilizing yield response and STK information compare to (1) short-term profit-maximizing K fertilizer rates that add crop price and fertilizer cost information, and (2) long-term profit-maximizing K rates that also value STK changes over time. The comparison involved estimation of yields, profitability, STK, and fertilizer

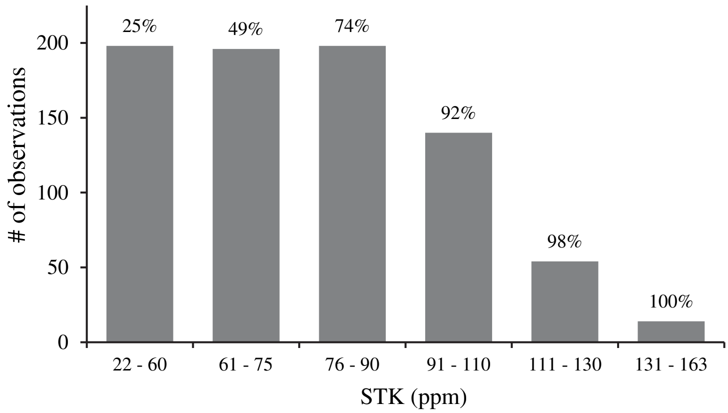

Figure 1. Frequency distribution of Mehlich-3 extractable soil-K (STK) concentrations (ppm) in the top 0–4 inch (0–10 cm) soil layer of a Calhoun silt loam across K-rate treatments from 0–160 lbs K_2O/ac in a rice/soybean 2-year crop rotation at the Pine Tree Research Station, AR, 2000–2020. Note: Labels above the bar indicate the cumulative likelihood of STK $\leq$ the upper limit of the bin interval. Minimum and maximum are the lower and upper limit of bin extremes, respectively. The average observed STK was 76.5 ppm.

use over a simulated period of 10 years using historical crop prices and fertilization costs across the three rate recommendation ideologies. We also demonstrate whether initial STK plays a role in what ending period STK values will be and whether or not fertilizer ideologies impact production risk.

2. Materials and Methods

2.1. Experimental Data and Background on K-Fertilizer Rate Recommendations

Experimental data for this study were collected using a trial with eight blocks planted to a 2-year rice/soybean crop rotation over the period from 2000–2020 at the Pine Tree Experiment Station in Arkansas. The soil is mapped as a Calhoun silt loam, which tends to be less rich in K availability or STK when compared to clayey soils and thereby is opportune for analysis of a "build and maintain" approach to STK rather than a soil where STK could be mined. This data set included 840 individual treatment observations from 21 years of fertilizer response trials of which 800 were usable given STK data observations in 2008 were inexplicably high (likely due to measurement error) and thereby excluded.

Each plot was soil-tested annually in the late winter or early spring before planting to track effect of K fertilizer rate and crop production on STK. To isolate the long-term effects of varying K fertilizer rates and STK on yield response over time, other yield-limiting nutrients (N, P, Zn) were applied to ensure the crop could reach its yield potential. To evaluate the effect of K fertilizer on crop yield, annual K-rate treatments were arranged in a randomized complete block design with a zero rate control and 4 additional K fertilizer rate treatments, ranging from 0 to 160 lbs K_2O/ac in 40-lb increments.

Soil-test K values in the plots within this study ranged from very low to optimum levels by agronomic standards as portrayed in Table 1. As shown in Figure 1, the minimum observed STK was 22 ppm and the maximum was 163 ppm across all soil tests performed. Given the trial started with similar initial STK in each plot ($\overline{STK} = 80.5$ ppm, $\sigma_{STK} = 7.81$), each K-rate treatment was thus replicated eight times within a growing season over the course of 21 years. That is, rice was grown in even years, and soybean was grown in odd years. Zero till using recommended seeding rate and weed control practices, commensurate for Mid-Southern U.S. row crops, were followed consistently.

Figure 2 summarizes annual crop yield and STK observations from 2000 through 2020 by K-rate treatment. The replicate average and standard deviation of rice yield for even years are

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depicted in the left column using the left-hand vertical axis. Using the right vertical axis, replicate average STK values are shown. Similarly, the average and standard deviation for soybean yield during odd years from 2001 to 2019 are depicted in the right column to showcase trends in yield and STK when K fertilizer was applied at different rates.

Over time, a slight increase in yields is observable for both crops as the fertilizer rate increased (Figure 2). For rice, STK values show a lesser linear downward trend when the fertilizer rate increased, while yields were simultaneously trending upward. In comparison, STK values for years when a soybean crop was in rotation, STK values eventually stabilized as the fertilizer rate increased (Figure 2). Hence, K fertilizer application rate influenced STK values with noticeable differences across crop grown.

Figure 3 showcases the same comparison but in terms of relative yield values, where a value of 100 implies the highest reported yield among varying fertilizer rates in a particular year and is defined further below. As STK was mined from the soil over time, especially in plots where no fertilizer was applied year after year, the relative yield trended downward at first while stabilizing near 70% after 2008. Even at the higher fertilizer rate of 120 lbs K_2O/ac per year, STK trended downward while RY values near 100 indicated yields near the maximal yield potential. This suggested that producers may only be able to maintain the level of STK, even at high rates of K fertilizer that exceeded the amount of K removed by the harvested grain, rather than build STK. Possible reasons for that are nutrient runoff or luxury consumption of K by the plant leading to greater K concentration in the harvested seed with higher K fertilizer use without a yield increase.

Also, the downward trend in RY over time in the no-fertilizer panel in Figure 3 coupled with the upward bu/ac yield at the various K-rate treatments depicted in Figure 2 suggests that supplemental K fertilizer allows producers to reach yield potential at low STK. Hence, allowing STK to drop over time did not sacrifice yield potential so long as K fertilizer could be added each year.

2.2. Yield Indices

Similar to Popp, Slaton, and Roberts (2020) and Popp et al. (2021), we calculate a relative yield index across K-rate treatments for estimation of a yield response to K fertilizer that, in a particular year, holds effects of management, crop cultivar, and planting date constant while removing weather and yield trend effects over time. Such effects otherwise present yield response estimation difficulties, when using actual crop yield, that are difficult to generalize to a variety of operating conditions. While a simplification, a crop grower's yield history, specifically yield potential, can now be used in conjunction with relative yield to estimate impacts of K fertilizer use on yield as explained in greater detail below. As such, we capture yield response to K by comparing observed yields (Y) each year under a specific crop rotation in a specific trial across the five K-rate treatments in this study and calculate an annual relative yield index value (RY) as follows:

$$RY_{crit} = \frac{Y_{crit}}{\max_j Y_{crit}} \cdot 100 \tag{1}$$

where c represents the crop under study (rice or soybean), r represents one of eight replicates, i represents the i^{th} of five fertilizer rate treatments including the no-fertilizer control (0 lbs of K_2O/ac), t represents a year from the range included in the data set of the particular crop, and j is the subset of four K-rate treatments excluding the no-fertilizer control treatment.

Thus, RY should take on values ranging from greater than 0 (crop failure due to K deficiency is unlikely) to 100, where the maximum observed yield for a specific replicate is highest among the other non-zero K-rate treatment plots and thus leads to an RY value of 100. However, the no-K control was excluded from the denominator in the RY calculation in equation (1), so RY values greater than 100 are possible in the case of a negative yield response to K fertilizer (which happened in six zero K plots early in the study mainly in rice and where STK was higher than average).

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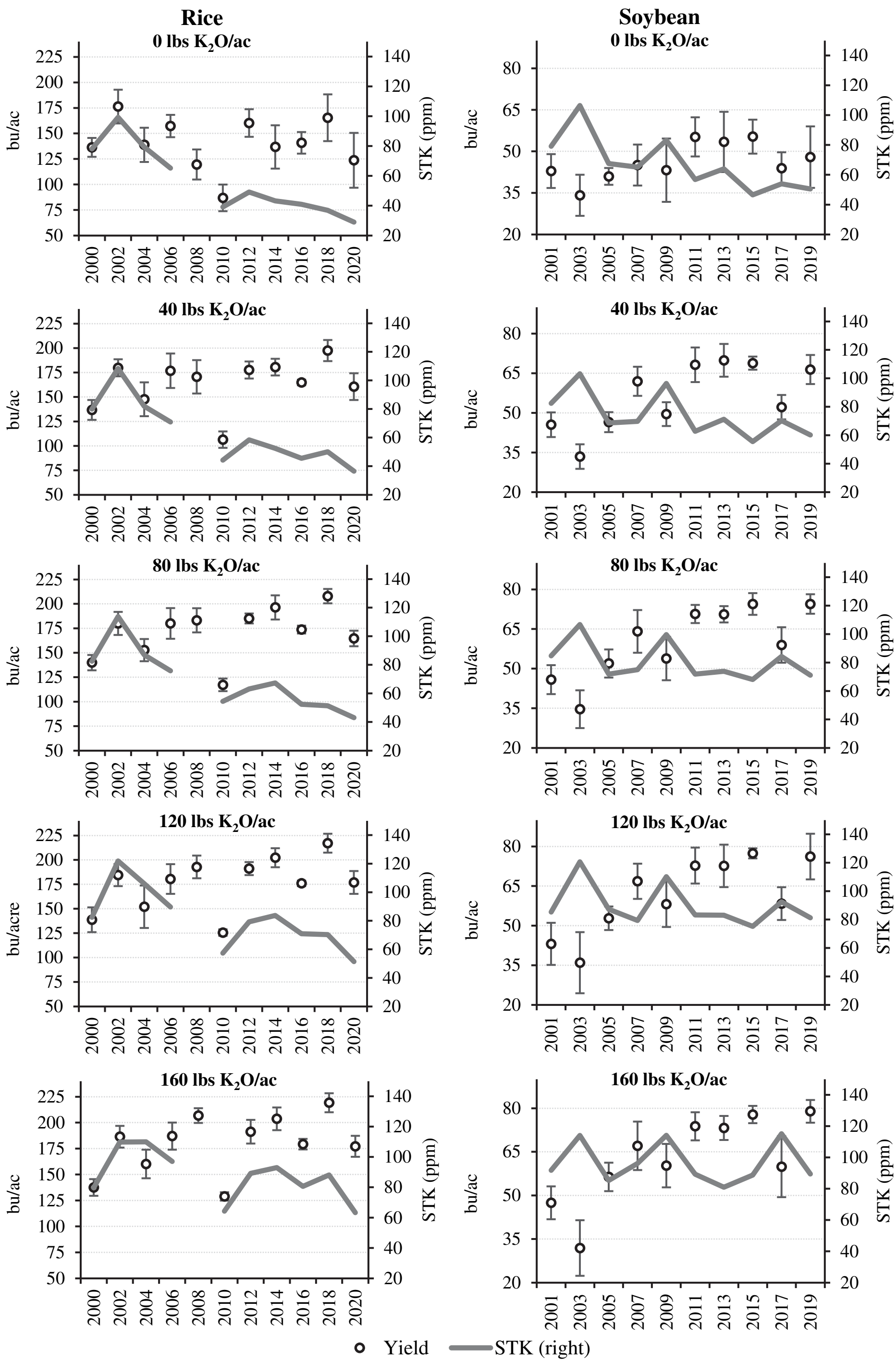

Figure 2. Average and standard deviation of yield for rice (left) and soybean (right) in bu/ac and average observed Mehlich-3 extractable soil-K (STK) concentrations (ppm) in the top 0–4 inch (0–10 cm) soil layer across different K-rate treatments. STK values for 2008 were judged unreliable and thereby excluded.

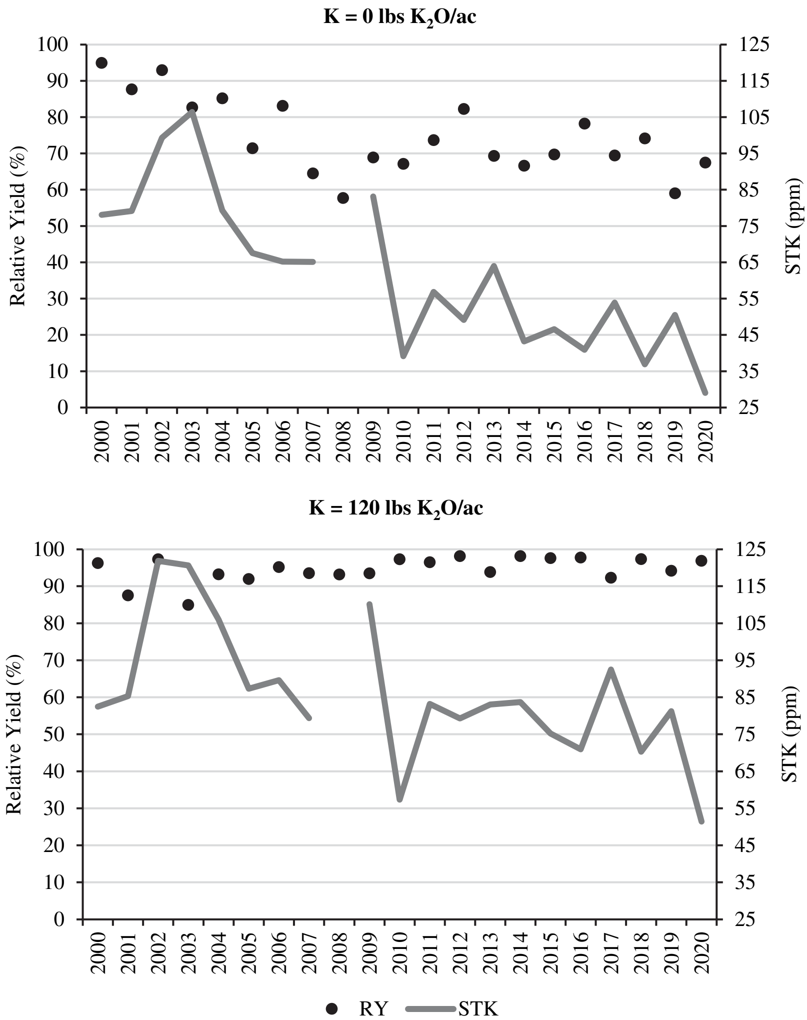

Figure 3. Replicate average relative yield values vs. Mehlich-3 extractable soil-K (STK) concentrations (ppm) in the top 0–4 inch (0–10 cm) soil layer in ppm from 2000–2020 for two of the five fertilizer K-rate treatments at the Pine Tree Research Station, AR. STK values for 2008 were judged unreliable and thereby excluded.

Since K is removed from a field in the harvested seed, a long-term yield index (YI) that compares yield values for a crop over time was also calculated to assess whether a particular crop year had relatively low or high yield in comparison to the long-term trend for a particular K-rate treatment and crop and thereby would remove relatively less or more K in the harvested seed. At the same time, the index also has the same meaning across crops as opposed to actually observed crop yields since rice yields are typically up to three times higher in bu/ac than soybean yields as shown in Figure 2. With YI, the impact of a relatively high or low yield in the prior year is reflected by comparing a particular crop's annual yield against their long-term average per K-rate treatment as follows:

$$YI_{crit} = \frac{Y_{crit}}{\sum_{t=1}^{21} \sum_{r=1}^{8} Y_{crit}/n} \cdot 100 \tag{2}$$

where c represents a specific crop (rice or soybean), r is one of 8 replicates, and t represents a year from the range included in the data set of the particular crop such that n amounts to a

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maximum of 80 observations[1] for 8 replicates for a K-rate treatment across ten years when soybean was grown and a maximum of 88 observations for 11 years when rice was grown, and i represents any one of the five K-rate treatments.

2.3. Soil-test K and Relative Yield Regression Methodology

Using the single-site, long-term data afforded insight about the impacts of changing K fertilizer rates on STK over time. The level of initial STK in the soil in the current year is a function of the previous year's STK, the rate of K fertilizer applied the last year, and the amount of K removed in the prior year's crop as measured by YI as follows:

$$STK_t = \alpha_0 + \alpha_1 STK_{t-1} + \alpha_2 K_{t-1} + \alpha_3 YI_{t-1} + \alpha_4 YI_{t-1} \cdot Rice_{t-1} + \delta_t + \varepsilon_t \tag{3}$$

where t represents a year from the range included in the data set of the particular crop, YI represents the yield index across K-rate treatments for a particular crop over time from equation (2), and *Rice* is a binary crop value (Rice = 1 when crop grown is rice and 0 = soybean) as rice and soybean have different K concentrations in harvested seed. Finally, δ_t are replicate random effects and ϵ_t is an error term. We dropped the K-rate treatment, replicate and crop subscripts for ease of presentation.

As yield data for this rice/soybean rotation study were collected over a 21-year period from 2000 to 2020, a number of factors could affect the yield response to K fertilizer as indicated above. Regressing RY, as calculated in equation (1), isolates the effect of K fertilizer on yield as the same cultivar was used across all K-rate treatments in a particular year, and all plots experienced the same weather. Hence, regressing RY on STK and K fertilizer (K) will essentially capture the long-term effect of K fertilizer rate across a range of observed yields, field-specific STK, and commonly used crop cultivars while still needing to control for crop-specific differences in yield response to K fertilizer. Therefore, long-term RY response to K, contingent on STK, was estimated for rice and soybean using:

$$\begin{aligned} RY_{rit} = {} & \beta_0 + \beta_1 K_{rit} + \beta_2 K_{rit}^2 + \beta_3 STK_{rit} + \beta_4 STK_{rit}^2 + \beta_5 K_{rit} \cdot STK_{rit} \\ & + \beta_6 K_{rit} \cdot STK_{rit}^2 + \beta_7 K_{rit}^2 \cdot STK_{rit} + \beta_8 K_{rit}^2 \cdot STK_{rit}^2 + \beta_9 Rice_{rit} \\ & + \beta_{10} Rice_{rit} \cdot K_{rit} + \beta_{11} Rice_{rit} \cdot K_{rit}^2 + \beta_{12} Rice_{rit} \cdot STK_{rit} \\ & + \beta_{13} Rice_{rit} \cdot STK_{rit}^2 + \beta_{14} Rice_{rit} \cdot K_{rit} \cdot STK_{rit} + \beta_{15} Rice_{rit} \cdot K_{it} \cdot STK_{rit}^2 \\ & + \beta_{16} Rice_{rit} \cdot K_{rit}^2 \cdot STK_{rit} + \beta_{17} Rice_{rit} \cdot K_{rit}^2 \cdot STK_{rit}^2 + \mu_{rit} + \rho_{rit} + \tau_{rit} \end{aligned} \tag{4}$$

where the constant term β_0 is the base RY value that did not change with year (t), K fertilizer rate applied (i), or replicate (r); β_1 and β_2 represent the average linear and non-linear, year- and plot-independent, coefficients of K fertilizer as measured in lbs of K_2O/ac; β_3 and β_4 are the average linear and non-linear coefficients on soil-test K (STK) as measured in ppm on RY; β_5 to β_8 represent the coefficients for the two-way interactions between STK and K; β_9 is the crop-specific intercept shifter for RY when rice is grown (rice = 1; soybean = 0); β_{10} and β_{11} represent coefficients for the crop dummy variable interactions with linear and non-linear forms of K; β_{12} and β_{13} represent coefficients for the dummy variable interactions with linear and non-linear forms of STK; β_{14} through β_{17} represent the coefficients for three-way interactions between the dummy variable with linear and non-linear forms of both K and STK; random effects for period and replicate are captured through μ_{rit} and ρ_{rit}, respectively, and τ_{rit} is a normally distributed random error term independent of two random effects.

[1]As shown in the supplemental material, some yield observations were missing. Unreliable STK data were not considered a reason for exclusion of yield data and, as such all available yield data were used to calculate long-term average yields across replicates for each K-rate treatment.

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Table 2. Statistical results comparison using time-lagged Mehlich-3 soil-test K (STK_{t-1}), fertilizer K application rate (K_{t-1}), yield index ($YI_{t-1}{}^{a}$), and yield index by crop interaction (Rice) to explain the current time period STK from 716 individual treatment observations of trials conducted from 2000 to 2020 (excl. 2008) in eastern Arkansas under an irrigated rice and soybean rotation using panel least squares regression with replicate random effects or systems estimation using ordinary least squares

Model Specification	Panel Least Squares (PLS)	System of Equations
Explanatory Variable[b]	Coefficient Estimate (SE[c])	Coefficient Estimate (SE)
Constant (α_0)	57.61 (6.27)***	54.86 (4.01)***
STK_{t-1} (α_1)	0.34 (0.05)***	0.37 (0.03)***
K_{t-1} (α_2)	0.13 (0.01)***	0.13 (0.01)***
YI_{t-1} (α_3)	−0.28 (0.04)***	−0.26 (0.03)***
Rice · YI_{t-1} (α_4)	0.13 (0.01)***	0.14 (0.01)***
Adj. R^2 in %	45.38	47.01

[a]Yield Index calculated using equation (2).
[b]Lag of observed soil-test K concentrations as defined by Mehlich-3 extractable soil-K concentrations in ppm (STK_{t-1}), lag of fertilizer K application rate (K_{t-1}) in lbs K_2O/ac, lagged temporal yield index (YI_{t-1}), and interaction with bivariate crop (Rice = 1 for rice and 0 for soybean). Coefficient estimate descriptors, α, are provided in parentheses to show the link to equation (3).
[c]The coefficient covariance matrix was adjusted using White's cross-section option when using PLS. Statistical significance: *$p < .05$, **$p < .01$, ***$p < .001$.

We also considered that estimating changes in STK and RY should be accomplished by using a system of equations as the current year's STK value is a regressor in equation (4) and the dependent variable in equation (3). Alternatively, equation (4) could be run separately for each crop using even years for rice and odd years for soybean. We later report those results in Tables 2 and 3.

2.4. Statistical Methods and Goodness of Fit

Equations (3) and (4) were estimated using various estimation methods employing EViews v. 9.5 (Lilien et al., 2015) and Stata (StataCorp, 2021). Results for each equation were first analyzed using ordinary least squares (OLS) to determine variables that increased the explanatory power of the model ($|t\text{-stat}| > 1$), decreased the Akaike Information Criterion (AIC), and enhanced adj. R^2. Improvement in AIC was more important than higher adj. R^2 in light of stronger correction for the number of variables used with AIC than adj. R^2 to penalize overfitting the model. Finally, visual evaluation across different specifications was also employed to ensure sign and size of coefficients was commensurate with expectations of diminishing marginal returns to K fertilizer use.

Next, we estimated equations (3) and (4) simultaneously as an OLS system of equations. Since heteroscedasticity was an issue in initial OLS estimation of equations (3) and (4) using the Breusch-Pagan-Godfrey heteroscedasticity test ($p < .001$), and because modeling a system of equations using White's heteroscedasticity-consistent estimators was not an available option in EViews®, R or Stata, we considered alternative separate estimation approaches for equations (3) and (4). Panel least squares with period and replicate random effects using Stata was deemed appropriate to estimate robust standard errors by adjusting the coefficient covariance matrix of equations to account for heteroscedasticity. For equation (3), we used replicate random effects only as the lagged dependent variable was among explanatory variables. For equation (4), we estimated yield response using a specification with a binary crop dummy variable as well as crop-specific estimations to assess alternative modeling approaches. We also pursued crop-specific equations with a single K by STK interaction and without STK^2 at a reviewer's suggestion.

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Table 3. Statistical results explaining relative yield (RY[a]) of rice and soybean as a function of fertilizer rate (K) and soil-test K (STK) based on 2000–2020 research trials (excl. 2008) in eastern Arkansas using panel least squares, ordinary least squares with a system of equations, and crop-specific panel least squares with period and replicate random effects

Model Specification	Panel Least Squares (PLS)	System of Equations	Soybean (PLS)		Rice (PLS)
Explanatory Variable[b]	Coefficient Estimate (SE[c])	Coefficient Estimate (SE)	Coefficient Estimate (SE)	Expl. Var.[b]	Coefficient Estimate (SE)
Constant (β_0)	40.20 (4.30)***	34.14 (4.11)***	26.93 (11.77)*	Const. (δ_0)	52.44 (7.56)***
K (β_1)	0.84 (0.12)***	1.06 (0.10)***	1.53 (0.49)**	K (δ_1)	0.77 (0.16)**
K^2 (β_2)	-2.67×10^{-3} (7.31×10^{-4})***	-2.95×10^{-3} (5.61×10^{-4})***	-6.17×10^{-3} (3.18×10^{-3})*	K^2 (δ_2)	-2.64×10^{-3} (1.03×10^{-3})**
STK (β_3)	0.55 (0.13)***	0.82 (0.11)***	0.92 (0.34)**	STK (δ_3)	0.69 (0.20)***
STK^2 (β_4)	-1.27×10^{-3} (1.09×10^{-3})	-3.49×10^{-3} (8.00×10^{-4})***	-3.14×10^{-3} (2.39×10^{-3})	STK^2 (δ_4)	-2.61×10^{-3} (1.40×10^{-3})
$K \cdot STK$ (β_5)	-9.11×10^{-3} (1.39×10^{-3})***	-1.33×10^{-2} (1.78×10^{-3})***	-2.53×10^{-2} (1.24×10^{-2})*	$K \cdot STK$ (δ_5)	-1.25×10^{-2} (3.98×10^{-3})**
$K \cdot STK^2$ (β_6)	1.89×10^{-5} (9.70×10^{-6})*	3.73×10^{-5} (9.54×10^{-6})***	1.07×10^{-4} (7.61×10^{-5})	$K \cdot STK^2$ (δ_6)	4.84×10^{-5} (2.56×10^{-5})
$K^2 \cdot STK$ (β_7)	2.29×10^{-5} (8.62×10^{-6})**	2.79×10^{-5} (6.72×10^{-6})***	1.08×10^{-4} (7.83×10^{-5})	$K^2 \cdot STK$ (δ_7)	4.35×10^{-5} (2.39×10^{-5})
$K^2 \cdot STK^2$ (β_8)	na[d]	na	4.68×10^{-7} (4.72×10^{-7})	$K^2 \cdot STK^2$ (δ_8)	-1.60×10^{-7} (1.42×10^{-7})
Rice (β_9)	13.76 (2.02)***	12.35 (1.22)***	na		na
Rice $\cdot$ K (β_{10})	−0.16 (0.03)***	−0.26 (0.05)***	na		na
Rice $\cdot K^2$ (β_{11})	6.58×10^{-4} (1.72×10^{-4})***	na	na		na
Rice $\cdot K \cdot STK^2$ (β_{15})	na	1.77×10^{-5} (6.27×10^{-6})**	na		na
Rice $\cdot K^2 \cdot STK$ (β_{16})	na	2.30×10^{-5} (7.65×10^{-6})**	na		na
Rice $\cdot K^2 \cdot STK^2$ (β_{17})	na	-2.05×10^{-7} (8.04×10^{-8})*	na		na
Adj. R^2 in %	60.74	55.15	53.79		70.55
# of obs.	795	795	396		399

[a]Relative Yield calculated using equation (1).
[b]Observed soil-test K concentrations as defined by Mehlich-3 extractable soil-K concentrations in ppm (STK), fertilizer K application rate (K) in lbs K_2O/ac, and binary variable Rice = 1 when rice is grown and 0 otherwise. Coefficient estimate descriptors, β and δ, are provided in parentheses to show the link to equations (4) and (6) with appropriate modifications.
[c]Numbers in parentheses are panel robust White's standard errors. Statistical significance: *$p < .05$, **$p < .01$, ***$p < .001$.
[d]na = not applicable given explanatory variable was removed due to lack of explanatory power or not applicable given model specification.

Using multiple K by STK interactions, however, allows the substitute vs. complimentary relationship between K and STK to vary as proximity and timing of nutrient access by plant roots and luxury consumption of K can impact that relationship in a given year and at varying levels of K and STK.

Finally, multicollinearity was not an issue between variables K and YI in equation (3) [(Pearson's correlation coeff. $\rho = -0.0143$), K and STK ($\rho = 0.4659$), YI and STK ($\rho = -0.1224$), or YI and Rice ($\rho = 0.0246$)]. There was also minimal multicollinearity between K and STK in equation (4) ($\rho = 0.4694$), K and Rice ($\rho < .0001$) and STK and Rice ($\rho = -0.2213$).

2.5. Economic Analysis

To calculate profit-maximizing K fertilizer use or K^*, the economic benefit of applying an additional lb/ac of K_2O fertilizer in terms of marginal revenue from added yield given crop price, P_c, in a particular year, t, and for a producer, p, was:

$$MR_{cp} = \frac{\partial RY_c}{\partial K} \cdot YP_p/100 \cdot P_{ct} \tag{5}$$

where the partial derivative of equation (4) is:

$$\begin{aligned}\frac{\partial RY_c}{\partial K} &= (\beta_1 + Rice \cdot \beta_{10}) + 2 \cdot (\beta_2 + Rice \cdot \beta_{11})K \\ &+ (\beta_5 + Rice \cdot \beta_{14})STK_s + (\beta_6 + Rice \cdot \beta_{15})STK_s^2 \\ &+ 2 \cdot (\beta_7 + Rice \cdot \beta_{16})K \cdot STK_s + 2 \cdot (\beta_8 + Rice \cdot \beta_{17})K \cdot STK_s^2\end{aligned} \tag{6}$$

and varies by crop using the *Rice* dummy variable and STK in a particular field (s). For the crop-specific models, the parameter estimates β_1 through β_8 remain, whereas the $Rice \cdot \beta_{10}$ through $Rice \cdot \beta_{17}$ estimates were dropped for the soybean model. A separate rice equation replaces estimates β_1 through β_8 with δ_1 to δ_8, respectively. The latter crop-specific estimation also allowed for estimation of different functional forms (quadratic in both K and STK, square root in both K and STK, as well as combinations of the two).

The second component of equation (5), YP or yield potential in a field, converts the marginal physical product expressed in terms of relative yield to actual yield impacts [recall equation (1)]. For this long-term analysis, we use the average rice and soybean yield as yield potential from the K-rate treatments that applied at 120 lbs K_2O/ac each year. At that level of K fertilizer use, yield response to further K was found to be minimal in prior studies for both crops (Popp et al., 2020, 2021). Therefore, YP for rice and soybean producers in this analysis were 176.20 and 61.75 bu/ac, respectively.

The third component of equation (5), P_{ct}, leads to marginal revenue product obtained at varying levels of STK and K when sufficient N, P, and/or Zn deficiency was managed as indicated above. Equating marginal revenue product to marginal fertilizer cost now leads to profit-maximizing conditions to obtain the profit-maximizing K fertilizer rate, K^*.

We solve for the rate at which the diminishing marginal revenue received from adding K is equal to the per unit cost of K, c_K, as follows:

$$K_{ts}^* = \frac{c_{Kt}}{\frac{YP_p}{100} \cdot P_{ct}} - \frac{\left[(\beta_1 + Rice \cdot \beta_{10}) + (\beta_5 + Rice \cdot \beta_{14})STK_{ts} + (\beta_6 + Rice \cdot \beta_{15})STK_{ts}^2\right]}{\left[2 \cdot \left(\beta_2 + Rice \cdot \beta_{11} + (\beta_7 + Rice \cdot \beta_{16})STK_{ts} + (\beta_8 + Rice \cdot \beta_{17})STK_{ts}^2\right)\right]} \tag{7}$$

Equation (7) assumes that the cost per unit of fertilizer does not change as K^* changes. That is, application costs per acre to apply fertilizer do not differ whether applying at low or high K fertilizer rates. However, c_K, the cost of fertilizer and crop price, P_c, will vary over time as does STK in producer field s and yield potential for individual producers p. Similar adjustments, as those made to equation (6) for using crop-specific equations, were made to equation (7) and are similar to those used in Popp, Slaton, and Roberts (2020) and Popp et al. (2021).

In summary, we expect that higher rates of K fertilizer over time could lead to increases in STK over time ($\alpha_2 > 0$) and that relatively high yields over time would negatively impact STK ($\alpha_3 < 0$) in equation (3) with lesser mining of K in rice due to lesser K removal in rice seed than soybean seed ($\alpha_4 > 0$). Because both K and STK affect the shape and slope of the yield response curve in equation (4), we use STK · K interaction terms to determine their relationship as well as the interaction by crop. We expect diminishing positive yield response to K with greater STK, as in previous studies. We also expect that crop price will positively impact the profit-maximizing K fertilizer rate, whereas fertilizer cost would have the opposite effect when making annual fertilizer decisions.

2.6. Changes in *STK* Over Time

Changes in STK as estimated using equation (3) hinge on prior year STK estimates, K fertilizer use, and resultant yield or relative yield estimates. As such, yield response functions for rice and soybean using equation (4) from the single-site data could be compared to prior modeling efforts using multi-site, short-term trial data (Popp, Slaton, and Roberts, 2020; Popp et al., 2021) to assess differences between a single-site long-term study to one that employed multiple sites. Assuming yield responses are similar, a next step is to calculate changes in STK to assess how yields and fertilizer use impact STK change.

A necessary step to track changes in STK over time is the conversion of RY estimates to YI values in equation (3). Recall that the RY value provides an index of yield values across the various K-rate treatments under study in a particular year, whereas the YI value is an index value of rice and soybean yields over a span of time. To make this conversion, the following equation is used:

$$YI_{K_c^*} = YE_{ct}/YP_c \tag{8}$$

where YE is the yield estimate in bu/ac of the crop (rice or soybean depending on crop rotation year) and fertilizer use (K_c), whereas YP represents the constant yield potential used for each crop at K = 120 lbs/ac. Since YP_c is the yield potential and equivalent to the yield when RY = 100, $YI_{K_c}{}^*$ and $RY_{K_c}{}^*$amount to the same value.

In sum, we can use RY estimates at profit-maximizing K^* rates using either our single-site long-term yield response equations or those from prior studies, to plug in as YI estimates for calculating changes in STK using equation (4). This allows for comparison of fertilizer rate recommendation ideologies, heretofore not possible as long-term changes in STK could not be estimated.

2.7. Profitability Differences Across Short-Term Rate Recommendations

To assess profitability impacts across fertilizer rate recommendation ideologies each year, partial returns (PR) to applying K^* (subscripts for year and trial site are again dropped from this point forward for readability) can be calculated as follows:

$$PR_{K_c^*} = YP_c \cdot \widehat{RY_{K^*}} \cdot P_c/100 - \widehat{K^*} \cdot c_K - K_{cust} \tag{9}$$

where the cost of fertilizer and its custom application cost (K_{cust}) are deducted from the revenue generated by crop sales. Further, current agronomic fertilizer rate recommendations (K_E) can be evaluated for PR by using K_E in lieu of $\widehat{K^*}$ and the estimated relative yield $\widehat{RY_{K_E}}$ with K_E in lieu of the estimated relative yield $\widehat{RY_{K^*}}$ with $\widehat{K^*}$.

Using historical crop and fertilizer prices from 2011 through 2020, we captured annual profitability differences when applying fertilizer at K^* using previously published multi-site yield response curve models versus the K_E rates from Table 1. We justify use of the previously published multi-site yield response curves on the basis of greater generalizability of model outcomes as discussed above and also because yield response to K fertilizer did not differ substantially (explained further below) between the single-site long-term data from the previously published results.

Using equation (3), we estimated changes in STK as a function of lagged STK, $K^*(K_E)$, and $\mathrm{YI}=\widehat{RY}$ on a field s, with three different starting STK. Further, we calculated the discounted sum of PR or the net present value (NPV) of annual PR to estimate the overall impact of the two different rate recommendation ideologies (current extension recommendations K_E vs. profit-maximizing single-period K^*) with different initial STK (not subscripted) on profitability using:

$$NPV_{K^*/K_E}=\sum_{t=1}^{10}\frac{PR_{t,K^*/K_E}}{(1+d)^t} \tag{10}$$

where d represents a selected discount rate and K^*/KE represent the different fertilizer rate recommendations, $t=1$ in 2011 and 10 in 2020. We expect NPV to differ across fertilizer application ideology as the K^*rates use crop price and fertilizer cost information, whereas K_E uses the same yield response information but provides rate recommendations by STK category as shown in Table 1.

2.8. Accounting for Stock Value of STK

While K_E recommendations were developed to "build and maintain" STK, K^* rates essentially ignore valuation of STK. As such, we used mathematical programming available in Excel® to value changes in STK as follows:

$$\max_{K_t} NPV_K=\sum_{t=1}^{10}\frac{PR_{c,t,K}}{(1+d)^t}, \tag{11}$$

where

$$PR_{c,t}=YP_{Soy}\cdot P_{c,t}\cdot$$

$$\frac{\begin{pmatrix}59.54+0.52K_t-1.61\cdot 10^{-3}K_t^2+0.35STK_t-7.62\cdot 10^{-4}STK_t^2\\ -4.76\cdot 10^{-3}K_t\cdot STK_t+1.03\cdot 10^{-5}K_t\cdot STK_t^2+1.42\cdot 10^{-5}K_t^2\cdot STK_t-3.07\cdot 10^{-8}K_t^2\cdot STK_t^2\end{pmatrix}}{100}$$

$$-K_t\cdot c_{K,t}-K_{cust}\,\forall t \text{ if } c=\text{Soybean}$$

(Source: Popp, Slaton, and Roberts, 2020)

$$PR_{c,t}=YP_{Rice}\cdot P_{c,t}\cdot$$

$$\frac{\begin{pmatrix}11.75+1.37K_t-5.66\cdot 10^{-3}K_t^2-0.55STK_t+13.9STK_t^{0.5}\\ +9.17\cdot 10^{-3}K_t\cdot STK_t-.22K_t\cdot STK_t^{0.5}-4.13\cdot 10^{-5}K_t^2\cdot STK_t+9.70\cdot 10^{-4}K_t^2\cdot STK_t^{0.5}\end{pmatrix}}{100}$$

$$-K_t\cdot c_{K,t}-K_{cust}\,\forall t \text{ if } c=\text{Rice}$$

(Source: Popp et al., 2021)

$$STK_t=\alpha_0+\alpha_1 STK_{t-1}+\alpha_2 K_{t-1}+\alpha_3 YI_{t-1}+\alpha_4 YI_{t-1}\cdot Rice_{t-1}$$

subject to:

$$0\le K\le 160\,\mathrm{lbs}\,\mathrm{K_2O/acre}$$

such that K is the long-run, annual profit-maximizing fertilizer K rates that maximize NPV which in turn are a function of the same yield response function as that used for developing K^* while tracking STK as a function of K and RY = YI. In essence, this method accounts for the stock value of STK over the 10-year period, *ex post*, as price and cost information is known.

2.9. Methodology Summary

In sum, we use the same multi-site, generalizable yield response functions to K for soybean and rice to estimate profit-maximizing K rates and resultant yield estimates. We compare the yield estimates to yield potential from a single-site study at a yield-maximizing K rate of 120 lbs K_2O/ac. We subsequently model the impact of three different rate ideologies—single-period profit-maximizing K^*, vs. long-term profit-maximizing K over 10 years and current extension recommendations K_E—to estimate impact on changes in STK from equation (3). In addition to STK, yield, and K use changes, we summarize profitability implications over 10 years using NPV and assess production risk implications by examining the standard deviation of annual PR for the different strategies when using crop simulation with different starting points to offer insight about production risk exposure.

3. Results

3.1. Statistical Results

Statistical results from equation (3) showed coefficient estimates for all variables to be statistically significant at any conventional confidence level and to display expected signs using various estimation methods for predicting changes in STK (Table 2). While coefficient estimates and adj. R^2 were similar across estimation methods, coefficient standard error estimates are higher with panel least squares estimation with robust error terms. Since estimating a system of equations using panel least squares with replicate random effects was not possible, we conservatively used the panel least squares coefficient estimates with lesser R^2.

Statistical results for equation (4) with all regressors were not shown here but are available from the authors upon request. Since numerous variables were not statistically significant ($p < .05$) for this specification that included all three-way interaction terms, variables were excluded one by one as described above and resulted in the following final yield response equation specification:

$$\begin{aligned} RY_{rit} = {} & \beta_0 + \beta_1 K_{rit} + \beta_2 K_{rit}^2 + \beta_3 STK_{rit} + \beta_4 STK_{rit}^2 + \beta_5 K_{rit} \cdot STK_{rit} \\ & + \beta_6 K_{rit} \cdot STK_{rit}^2 + \beta_7 K_{rit}^2 \cdot STK_{rit} + \beta_9 Rice_{rit} + \beta_{10} Rice_{rit} \cdot K_{rit} \\ & + \beta_{11} Rice_{rit} \cdot K_{rit}^2 + \mu_{rit} + \rho_{rit} + \tau_{rit} \end{aligned} \tag{12}$$

Like equation (3), variables in equation (12) were statistically significant at any conventional confidence level, using either a system of equations or panel least squares approach (Table 3). However, crop-specific estimation methods with replicate and period random effects and robust error terms shown in the last two columns provided estimates that in terms of methodology were more compatible to estimation methods in prior studies (Popp, Slaton, and Roberts, 2020; Popp et al., 2021) and included all two-way interactions between K and STK as variables that added explanatory power to the models. The final model estimation technique chosen used the crop-specific equations since visual examination of response functions conformed best to expectations in comparison to the alternatives in Table 3 as well as crop-specific panel least squares estimation random effects and a single K by STK interaction (not shown but available from the author upon request).

Figure 4 shows the comparison of the chosen estimation methods (the last two columns in Table 3) to the yield response functions from prior studies (Popp, Slaton, and Roberts, 2020; Popp et al., 2021) using multi-site short-term trials. Yield responses at STK > 100 ppm, which

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were observed in the data less than 10% of the time (Figure 1), continued to show yield improvement and, in the case of rice, a response curve that started to deviate from expectations (note slightly U-shaped yield response curve in the bottom left panel). This suggested that relying on yield response curve estimates from a single location was not a practical solution.

Nonetheless, yield benefits from added K fertilizer for both crops diminish as STK increased. Using either single-site long-term data or multi-site short-term data for estimating yield response (Figure 4) and for the relevant range of STK observations, the Y-intercepts increased, and the curves became flatter the higher the STK. Since the dashed-line yield response curves using the single-site data were steeper compared to the solid-line response curves using the multi-site data, we would expect greater K^* using the single-site data in comparison to the multi-site data. Also noteworthy was that estimated RY were lower using the single-site data for soybean in comparison to the multi-site data for STK scenarios shown. Since K-rate treatments are repeated over a long period of time and plot-specific in single-site plots, the cumulative effect of the no-K control may have become larger over time than in multi-site plots in the sense that the difference in STK could be larger in the single-site trials across K-rate treatments than in fields selected in multi-site studies. This observation is deemed minor as no-K fertilizer use over an extended period of time is unlikely in a producer field setting but does showcase what is estimated to happen.

As already discussed during the data description, field evidence suggested that applying at high K fertilizer rates when producing rice and soybean may only modestly build STK (Figures 2 and 3). Luxury consumption of K by the plant, when available in excess, lessens the agronomic K use efficiency and could explain why no notable STK increase occurred at high annual K fertilization rates (Slaton, 2022). Nutrient loss via leaching, erosion, or runoff may also play a role as STK declined in Figure 3 despite relatively high K fertilization rates in the bottom panel. Such decay in STK impacts K use efficacy in the sense that the α_2 coefficient estimate in equation (3) potentially captures K losses to leaching, erosion, or runoff and/or luxury consumption of K. A specification of equation (3) with a trend variable was not used in this analysis as it rendered the crop yield removal effects (YI) coefficient, α_3, statistically insignificant. Since α_2 adequately captures the net K use efficacy toward building STK over time, we deemed inclusion of a trend variable less important in comparison to capturing yield removal effects with a significant α_3 coefficient estimate. Further details are available from the authors upon request.

In sum, irrespective of how similar yield responses are whether using single-site or multi-site data, the statistical significance of findings in Table 2 suggested that using previously published multi-site yield response functions and the single-site estimates for temporal STK changes was deemed appropriate.

3.2. Starting Stock Values of STK

When comparing impacts of applying at current agronomic rates (K_E) versus profit-maximizing fertilizer rates, using either short-term (K^*) or long-term (K) profit-maximizing rates, the choice of starting STK influences fertilizer rates. As such, we chose three values of beginning STK that were in the range of observations from the single-site data set (Figure 1) that corresponded to the average of very low, low, and medium agronomic ranges depicted in Table 1. We did not analyze the effects at higher beginning STK as K^* recommendations from earlier work led to economic thresholds to no longer apply supplemental K fertilizer when STK is above 96 ppm for rice (Popp et al., 2021) and 128 ppm for soybean (Popp, Slaton, and Roberts, 2020) using the most recent average 10-year crop price and fertilizer costs. Also, the yield response to K shown in Figure 4 suggests that yield potential (achieving RY > 95) is achievable at low STK. Hence, producers have little incentive to build STK since the chance for potential nutrient loss may increase with higher K application rates, and delaying fertilizer expenditures until needed would increase NPV.

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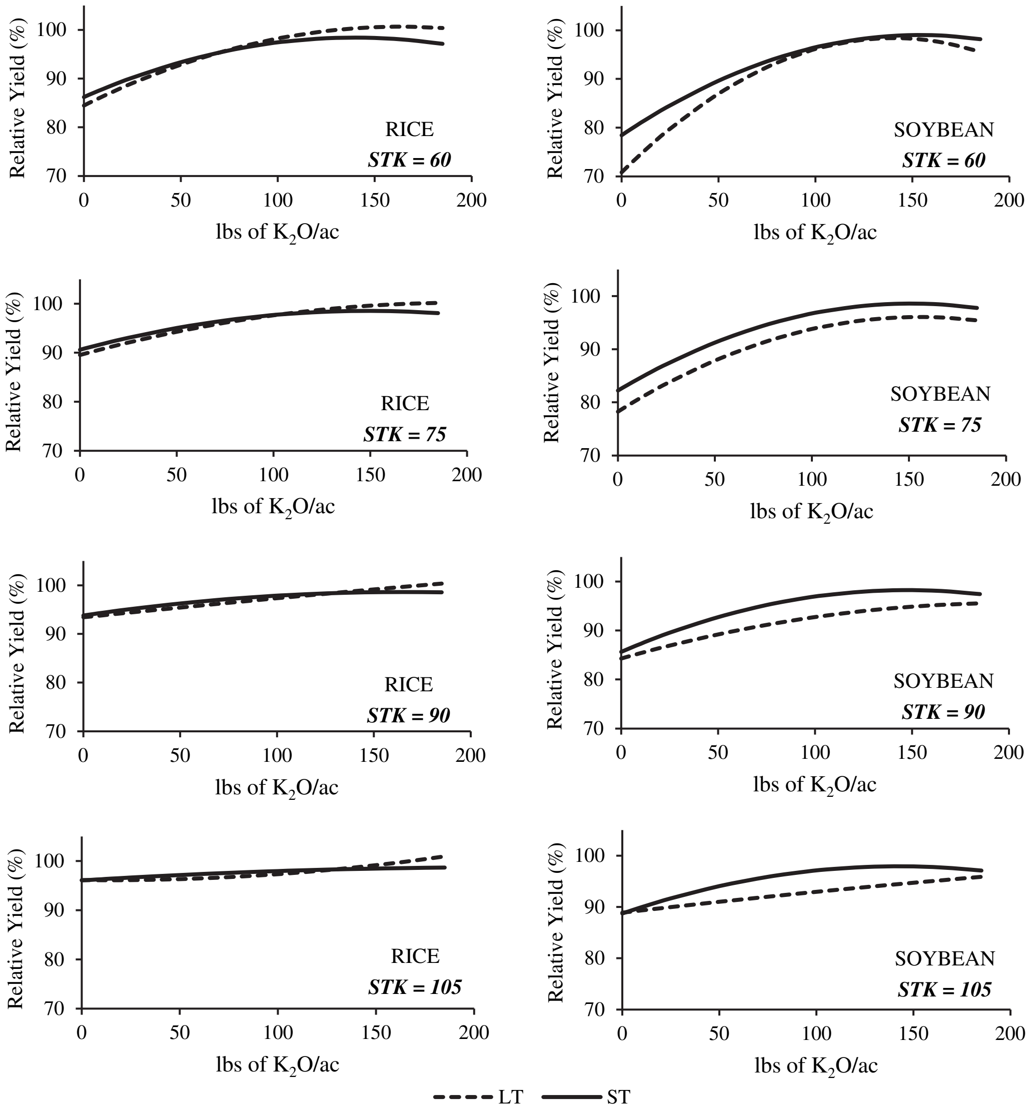

Figure 4. Comparison of estimated rice (left) and soybean (right) relative yield responses to fertilizer K rate at 60, 75, 90, and 105 ppm Mehlich-3 extractable soil-K (STK) concentrations (ppm) in the top 0–4 inch (0–10 cm) soil layer using long-term (LT), single-site and short-term (ST), multi-site data.

3.3. Simulation of Alternative Fertilizer Rate Recommendation Ideologies

Figure 5 summarizes K fertilizer application differences across recommendation ideologies using simulated yield data from 2011 to 2020 using annual observed crop prices and fertilizer cost as shown in the bottom right panel when rice is grown first. As discussed above, we started the simulation using different initial STK (shown as the trailing numbers in the legend) and applied fertilizer yield responses using the multi-site data for all scenarios. The K_E scenario applies K fertilizer at rates based on STK from Table 1 and is identified in the legend with the leading KE letters, whereas K^* uses STK, yield potential, yield response to K, expected crop price, and fertilizer cost or information that a producer would have each year. Finally, the long-term, profit maximization

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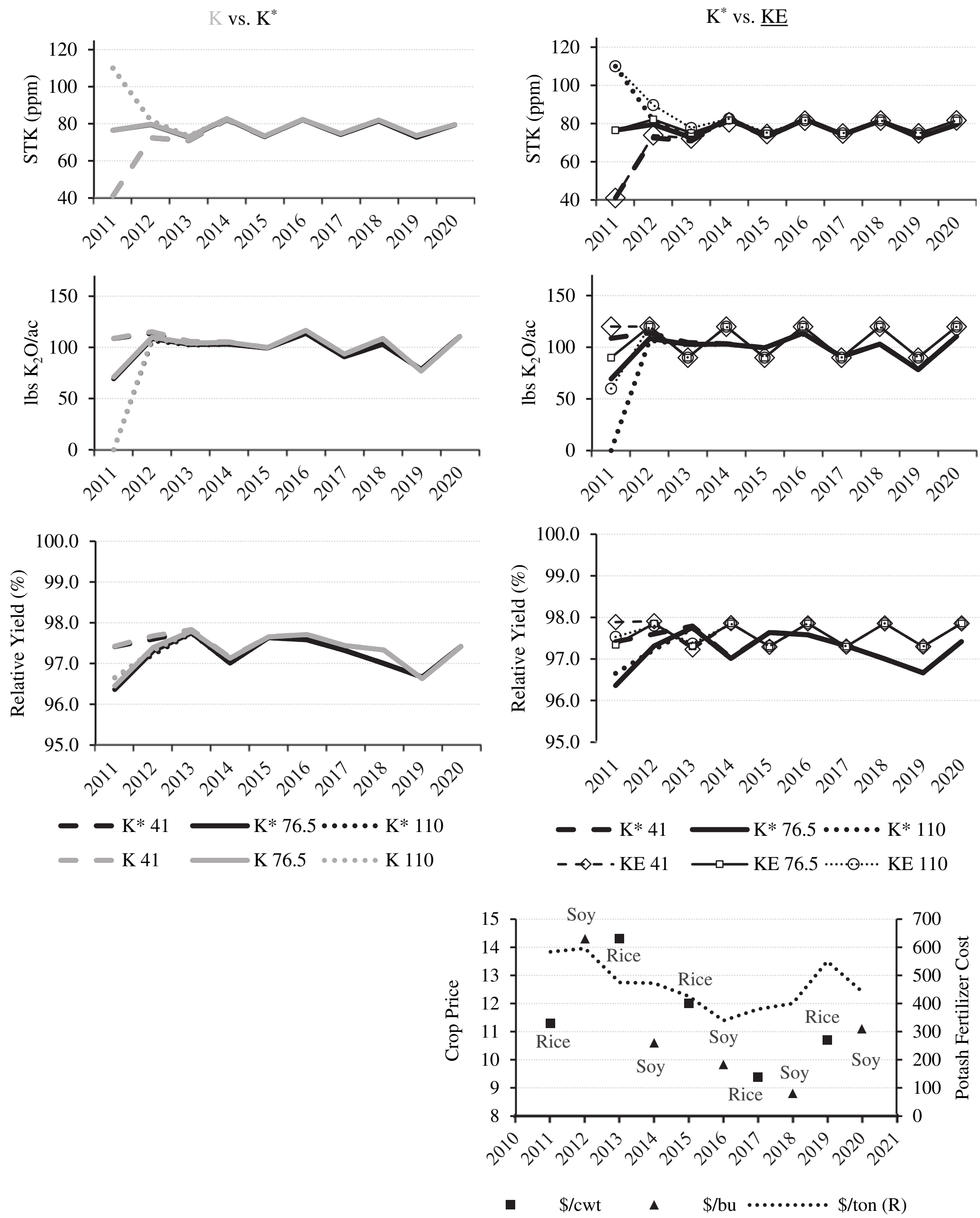

Figure 5. Graphical comparisons of using "long-term" (K) versus "short-term" (K^*) profit-maximizing K fertilizer rates (left column) and K^* vs. current recommendations (K_E) (right column) on Mehlich-3 extractable soil-K concentrations in ppm or STK (top panels) and K fertilizer rates (bottom panels) when initial Mehlich-3 extractable soil-K (STK) concentrations (ppm) started at 41, 76.5, or 110 ppm when rice is grown first.

K scenario assumes knowledge of crop price and fertilizer cost information over the period to assess how 10-year profits could be maximized with perfect information and accounts for stock value of STK. All scenarios use model results of equation (3) pertaining to changes in STK as a result of prior year information about yield, fertilizer use, and STK.

Resultant relative yields by crop are summarized in the bottom in the third row of panels of Figure 5, and the cumulative yield impact is reported in Table 4. Taking stock value of STK into account leads to slightly higher K use, attendant yields, and nearly identical ending STK (Figure 5 and Table 4). K_E fertilizer rates led to higher yields and used 120 lbs K_2O/ac on soybean and 90 lbs K_2O/ac on rice given convergence to STK values between 75 and 82 ppm in the top right panel of Figure 5. A notable exception is the first year, when $K_E = 60$ lbs K_2O/ac on rice for the scenario when initial STK was 110 ppm. By comparison, K and K^* recommendations vary more, given changes in crop price and fertilizer cost that impact fertilizer use. Application rates are generally lower than the K_E rate recommendations for soybean and higher than K_E for rice (second row of panels in Figure 5). As a direct consequence of lesser overall K use (top of Table 4), STK in 2020 is slightly lower with K and K^* than K_E recommendations over time.

The 2011, 2014, 2018, and 2019 fertilizer rate recommendation differences between profit-maximizing and K_E rates stand out. Compared to the 2011–20 average, soybean and rice prices in those years were historically low and fertilizer cost was relatively high in 2011 and 2019. As such, the profit-maximizing rates were substantially lower than the agronomic K_E recommendation leading to lower ending STK in 2020 (Table 4 and Figure 5). It is the lesser overall fertilizer K use with K^* in comparison to K_E that explains overall lower yields as reflected in lower average relative yield in the third row of panels in Figure 5. Less fertilizer use led to fertilizer cost savings and slightly lower yields with K^* compared to K_E, however, that translated to PR and NPV in Table 4 that slightly favor profit-maximation over K_E.

Comparisons between K^* and K rates point to nearly indistinguishably higher K use when taking stock value of STK into account. PR and NPV are nearly identical (Table 4). This suggested that the stock value of STK played a minor role using the 5% discount rate (a result that was essentially unchanged in terms of fertilizer K use when doubling the discount rate). The K recommendations in comparison to the K^* recommendations led to a minuscule increase in K fertilizer use translating to less than a bushel difference in total yields over the period (Table 4). The same is true between K^* and K_E. While profit and yield are nearly the same across fertilizer rate recommendations, using profit-maximizing K^* rates saved approximately 5–11% K fertilizer with ending STK values in the same agronomic bracket (Table 1). Finally, standard deviation of PR in a particular column in Table 4 indicated profit-maximizing rate choices to have nearly identical production risk in comparison to current extension recommendations.

3.4. Starting Crop in Crop Rotation

Similar results unfold when soybean is grown first. Short-term profit-maximizing fertilizer rates mirror those of slightly higher K-using long-term profit-maximizing choices. The K^* rates are lower than K_E rates by a smaller margin (3–4%), and NPV is again slightly higher (Table 4 and Figure 6). We attributed these changes to the timing of price changes as well as the greater responsiveness to K fertilizer with soybean (Figure 4). Fertilizer use was less volatile over time when soybean was the first crop when comparing the middle panels of Figures 5 and 6.

As such, it is noteworthy that most producers will grow both soybeans and rice in a particular year. With findings in terms of K use, profitability, and yield implications similar regardless of what crop is modeled first (Table 4), results for a producer are likely to occur between the two extremes shown in Figures 5 and 6 for this modeling period.

4. Conclusions

The objective of this study was to compare profitability, yield, and fertilizer use estimates across three different fertilizer rate recommendation ideologies. Existing agronomic, "build and maintain" fertilizer rate recommendations (K_E) are compared to those using profit-maximizing rates based on "short-term" insight using current market prices (K^*) over a ten-year period by

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Table 4. Simulated 2010–2020 K fertilizer use, ending soil-test K, overall yield, net present value (NPV) in 2010 dollars, and standard deviation of partial returns when applying at current agronomic (K_E) fertilizer rates versus short-term (K^*) and long-term (K) profit-maximizing fertilizer K rates where the latter accounts for the stock value of STK when rice (top) and soybean (bottom) are grown first with three alternative STK starting values (top row)

Metric	STK[a]	41			76.5			110		
	Scen.[b]	K_E	K^*	K	K_E	K^*	K	K_E	K^*	K
Rice followed by Soybean										
Total K (lbs K_2O/ac)		1,080	1,026	1,041	1,050	979	996	1,020	907	922
Ending STK (ppm)		81.6	79.4	79.5	81.6	79.4	79.5	81.6	79.4	79.5
Total Yield (bu/ac)		1,160	1,158	1,159	1,159	1,156	1,157	1,160	1,157	1,157
NPV_{2010}[c,d,e] ($/ac)		5,698	5,702	5,702	5,707	5,711	5,712	5,723	5,746	5,746
Std. Dev.[f] ($/ac)		174	174	174	175	175	175	176	177	177
Soybean followed by Rice										
Total K (lbs K_2O/ac)		1,090	1,046	1,060	1,050	1,011	1,027	990	956	976
Ending STK (ppm)		75.4	70.9	71.3	75.4	70.9	71.3	75.4	70.9	71.3
Total Yield (bu/ac)		1,160	1,161	1,162	1,159	1,159	1,160	1,158	1,158	1,158
NPV_{2010} ($/ac)		5,890	5,902	5,903	5,898	5,903	5,903	5,907	5,912	5,913
Std. Dev. ($/ac)		210	209	209	210	209	209	210	209	209

[a]All scenarios employ the multi-site yield response estimates to K fertilizer from prior studies. Agronomic "build and maintain" stepwise uniform rate recommendations are shown in Table 1. Short-term profit maximization ignores stock value of soil-test K (STK) using crop price and fertilizer cost. Long-term optimization, using equation (11), maximizes producer profit by taking stock value of STK into account and assumes producers have all information ahead of time.
[b]Columns are differentiated by varying initial STK in ppm. Note that STK is estimated to change over time as shown in Figures 5 and 6 using equation (3) based on yield and fertilizer use.
[c]Crop price for rice was $12.02/cwt on average and $10.81/bu for soybean (USDA, 2021a, 2021b) and are plotted over time in Figures 5 and 6 (bottom right).
[d]Fertilizer cost in $/ton for muriate of potash fertilizer (0–0–60), $466.34 on average, or $0.39/lb K_2O (MSBG, 2021). Fertilizer cost is plotted in Figures 5 and 6 (bottom right).
[e]Net present value (NPV) values are in $/ac and capture the discounted sum of annual partial returns to crop production over the period using a 5% discount rate [equation (10)]. Partial returns are based on yields, crop price, fertilizer cost, and fertilizer application charges of $7.50/ac in nominal terms [equation (9)]. Since the rice price is in $/cwt, we convert bu/ac to cwt/ac using 45 lb/bu for rough rice.
[f]Standard deviation of annual partial returns.

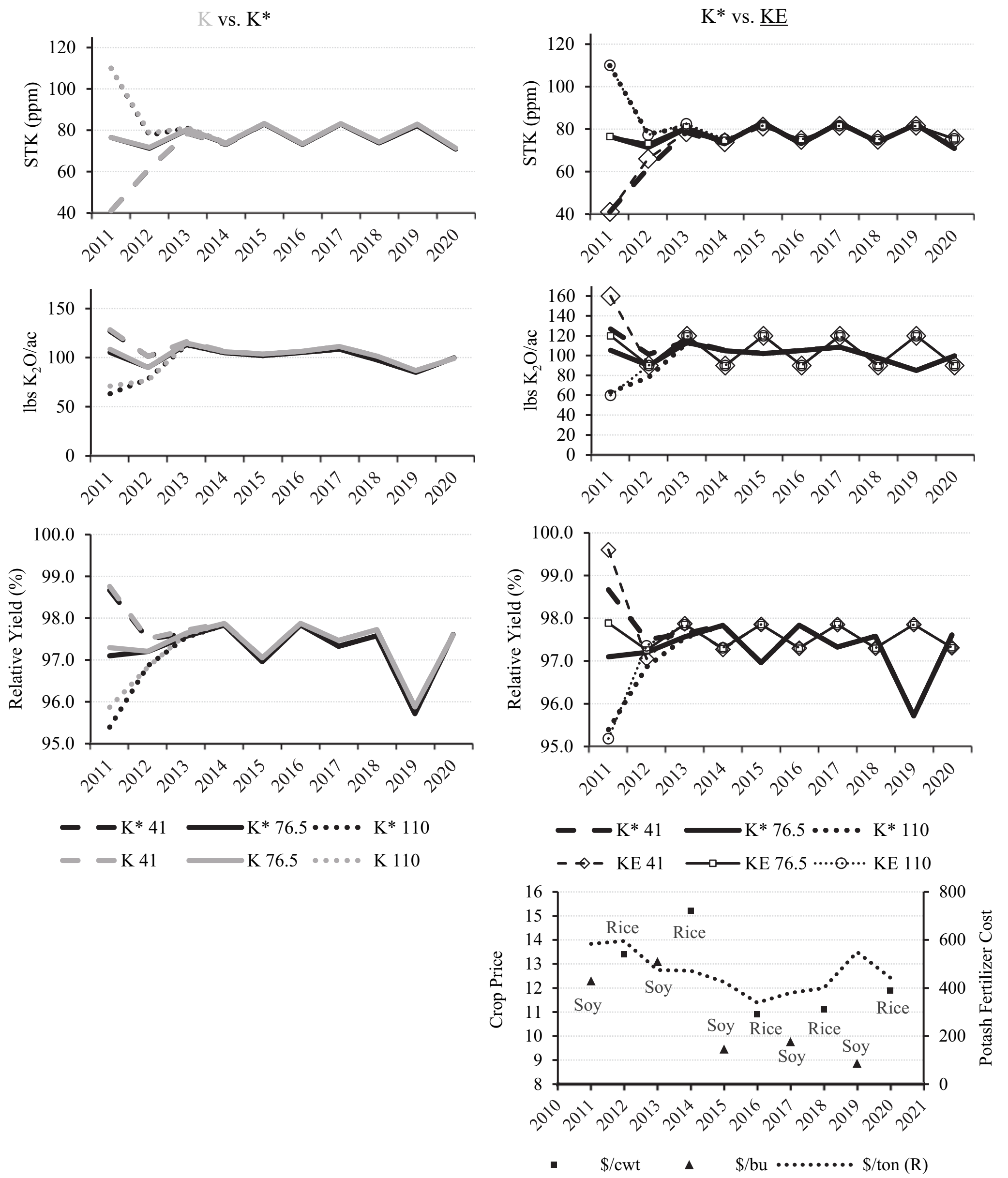

Figure 6. Graphical comparisons of using "long-term" (K) versus "short-term" (K^*) profit-maximizing K fertilizer rates (left column) and K^* vs. current recommendations (K_E) (right column) on Mehlich-3 extractable soil-K concentrations in ppm or STK (top panels) and K fertilizer rates (bottom panels) when initial Mehlich-3 extractable soil-K (STK) concentrations (ppm) started at 41, 76.5, or 110 ppm when soybean is grown first.

estimating the impact on STK from a single-site, long-term study. With the goal of maximizing K use efficiency both in terms of creating yield and in terms of profitability, we find that regardless of initial STK, estimated changes in ending STK using K fertilizer at K_E versus K^* versus long-term profit-maximizing K rates are minimal and depended more on crop sequence than rate recommendation philosophy (higher ending STK were observed when soybeans were grown in a particular year as rate recommendations are higher given greater yield response to K fertilizer in soybean than rice).

Both short-term (K^*) and long-term (K) profit-maximizing fertilizer rate recommendations move up and down because of crop price and fertilizer cost changes leading to STK values that move in concert with those obtained following K_E fertilizer rate recommendations (Figures 5 and 6). However, year-specific recommendations critically depend on crop price and fertilizer cost. Overall 10-year fertilizer use is highest with K_E followed by K and K^* rates, respectively. Profitability comparisons suggested that the use of K^* rates was optimal in the sense that least fertilizer is used, regardless of crop sequence, while attaining nearly identical profits as available with long-term profit maximization. As such, we argue that using the K^* framework, coupled with the existing decision aid to estimate profit-maximizing rates from prior studies (Popp, Slaton, and Roberts, 2020; Popp et al., 2021), is preferable over the use of the K framework given similar reactions to price and cost changes over time with only minimal change in ending STK given different starting STK.

Tracking estimated STK across the different ideologies was valuable in the sense that it showed that producers are likely to end at similar STK and at relatively low levels by agronomic standards. At the same time, incorporating crop price and fertilizer cost led to essentially the same level of profitability between the short-term profit-maximizing framework and the "build and maintain" framework while the former used approximately 3–11% less K fertilizer over the simulated 10-year period as summarized in Table 4 and Figures 5 and 6. Less fertilizer use also led to slightly lower yield and ending STK but higher profit in comparison to a "build and maintain" philosophy. With minable fertilizer resources finite, resource conservation and lesser potential for nutrient runoff are not valued within.

Hence, we argue that especially in years when crop price and fertilizer cost deviate largely from the norm, as in 2011 and 2019, the use of a decision aid is preferable to using current recommendations (Table 1) from both a profitability and K resource conservation perspective.

At the same time, we realize that further work is needed to model temporal STK changes across an array of more crop rotations and locations to gain greater insight. Economic risk implications of letting STK levels drop to the low agronomic range could also benefit from additional study perhaps using several different simulation periods. At least in the above example, risk implications of following a "sufficiency approach" using short-term profit-maximizing fertilizer rates did not impact standard deviation of PR in comparison to the agronomic "build and maintain" philosophy or the long-term profit-maximizing rate suggestions that value STK.

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