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Project Title:

Calibration of Soil Test Interpretations and Nutrient Recommendations for Major Commodities Grown Across Florida as a Best Management Practice for Sustainable Agriculture

Final Project Report- January, 2018

1. **Gainesville Report**
2. **Belle Glade (sand land) Report**
3. **Belle Glade-(muck soils) Report**
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Calibration of Soil Test Interpretations and Nutrient Recommendations for Major Commodities Grown Across Florida as A Best Management Practice for Sustainable Agriculture

Final Project Report

Background:

Proper fertilizer recommendations for agricultural crops based on a calibrated soil test can lead to efficient uptake of nutrients by crops, resulting in effective agricultural BMPs and minimize negative impacts on environmental quality. Adoption of new calibrated soil test methods will achieve long-term agronomic and environmental sustainability. Fundamentally speaking adoption and implementation of agricultural BMPs begins with a credible soil test.

Continuous calibration of the existing standard soil test methods and interpretations is critical for ensuring that both agronomic and environmental goals are met. Currently, the IFAS Extension Soil Testing program has identified Mehlich-3 as the most appropriate soil test extractant for a wide range of mineral soils of Florida (Mylavarapu, et al., 2014).

Objectives:

1) Scientifically defensible Mehlich-3 soil test calibrations for phosphorus and potassium conducted on a range of soils for major commodity crops, and
2) Scientifically defensible phosphorus and potassium fertilizer rates recommended based on the results of field tests.

The proposed multi-season field and complementary greenhouse studies aim to improve P and K recommendations based on Mehlich-3 soil tests, guiding BMP implementation and minimizing water quality impacts due to excessive nutrient applications. Complementary greenhouse studies will be conducted at most locations where facilities exist for creating controlled and simulated soil test levels to help determine plant uptake and dose response.

This field calibration work will be conducted in a multi-year and multi-location format to cover the major agricultural production regions and crops in the state of Florida.

Mehlich-3 soil test phosphorus and potassium calibration and Validation Field Trial in Marion County, Florida

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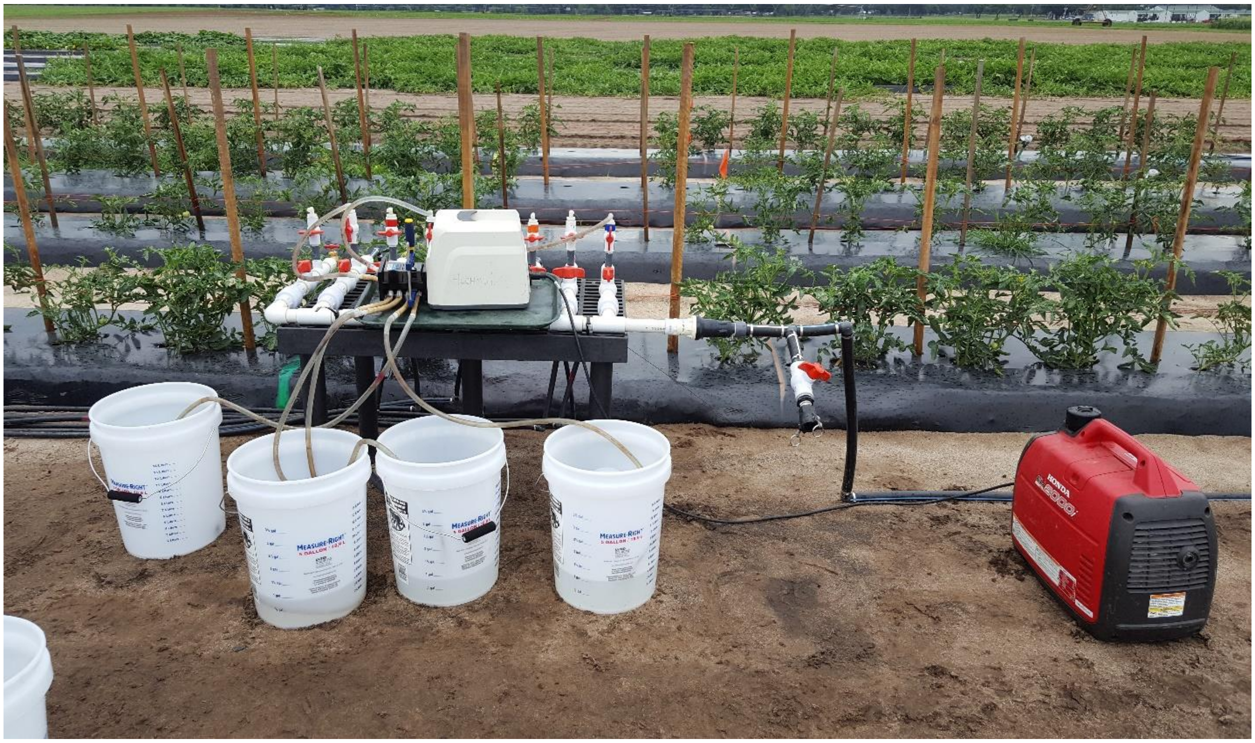
1.1 Site

The research was conducted in a research field at Plant Science Research and Education Unit, Citra, Florida. The soil was Gainesville loamy sand classified as Hyperthermic, coated Typic Quartzipsamments. The background soil phosphorus (152 mg kg^{-1}) and potassium (92 mg kg^{-1}) were high based on the Mehlich-3 soil test.

1.2 Materials and methods

The beds were covered with black plastic mulch with two drip tubing running under the plastic mulch. One tube was used for irrigation and the other tube was used for the application of fertilizers. Tomato variety BHN 602 was planted on 1st May 2017. Tomato beds were 5 feet apart and the plant to plant distance was maintained at 1.5 feet. Each plots were 22.5 feet long that accommodated 15 tomato plants. Tomato plants were planted in a single row.

Nitrogen was applied according to the standard IFAS recommendation. The IFAS nitrogen recommendation for tomatoes was 200 lbs/acre. Because, the soil was high in both phosphorus and potassium, fertilizer application was not recommended for both nutrients. The N rate was divided into 13 split application and the first N was applied one week after the planting and the subsequent rates are being applied in a weekly basis. Insect the disease control were also based on the IFAS standard practice. Phosphoric acid and muriate of potash were used as a source of phosphorus and potassium, respectively. The fertilizer materials for all the treatments were dissolved in 3 gallons of water in a plastic bucket and the dissolved fertilizer was applied to tomato plants through the fertigation system with the help of a pump (Picture 1). All the phosphorus was applied once at first treatment application on June 2nd and the potassium was applied at 3 split rates. The split rates of potassium were applied at 2nd June, 14 June and 26rd June.



Picture 1. Fertilizer application to tomato plants with the help of a pump

The tissue and soil samples will be collected at 30 days interval. The leaf samples included recently matured tomato leaves. The leaf samples will be dried in oven at 60°C and ground to pass through a 2 mm mesh size. The samples will the analyzed for phosphorus and potassium. Soil samples will be air dried in shade and will be analyzed for the two nutrients.

The experiment consists of 6 fertilizer treatments arranged in a randomized complete block design and replicated four times. The data were subjected to analysis of variance (ANOVA) to determine if some of the treatments resulted in significantly different result. Tukey mean separation test was used to determine the difference between treatments.

Table 1. Treatments detail of the experiment

Treatments	Detail
T1 (P1K1)	(P1K1): IFAS* P + IFAS K
T2 (P1K2)	(P1K2): IFAS P + (IFAS +25 lbs/acre K)
T3 (P1K3)	(P1K3): IFAS P + (IFAS +50 lbs/acre K)
T4 (P2K1)	(P2K1): (IFAS + 25 lbs/acre P) + IFAS K
T5 (P2K2)	(P2K2): (IFAS + 25 lbs/acre P) + (IFAS + 25 lbs/acre K)
T6 (P2K3)	(P2K3): (IFAS + 25 lbs/acre P) + (IFAS + 50 lbs/acre K)

*IFAS refers to standardized soil test recommendations by IFAS, University of Florida based on Mehlich-3 soil extraction method and interpretation.

Results

The tomato plants are currently in the fruit maturity stage as shown in the picture 2. Sample collection at 30 day after planting (DAP) has been performed. We have received the soil test results from the laboratory but the tissue results are yet to be received. Hence, 30 DAP soil test results are presented here in table 2. The results showed that there is no difference in both phosphorus and potassium content between the treatments. The soil samples were taken after a week of treatment application. Phosphorus applied as fertilizer rapidly reacts with other elements especially Calcium and Aluminum in the soil to form insoluble phosphorus compounds. These reactions can play important role in reducing the amount of available phosphorus in soil. Nutrient uptake by the growing plants may also reduce the available fraction of the phosphorus in the soil. Only one third of the recommended rate of potassium was applied before 30 DAP soil sampling. Potassium uptake by the growing plants may have reduced the available potassium in the soil so that the difference between the fertilized and unfertilized plots was equal.

Table 2. Soil phosphorus and potassium at 30 days after planting

Treat	Soil Phosphorus (mg kg^{-1})	Soil Potassium (mg kg^{-1})
T1 (P1K1)	139.9 a	50.3 a
T2 (P1K2)	128.7 a	49.1 a
T3 (P1K3)	149.2 a	38.3 a
T4 (P2K1)	135.2 a	44.0 a
T5 (P2K2)	137.6 a	37.9 a
T6 (P2K3)	142.5 a	41.0 a

The letters followed by the same letters in the column are not significantly different by Tukey procedure ($\alpha \leq 0.05$)

Picture 2. Tomato plants at fruit initiation stage

Mehlich-3 soil phosphorus and potassium were not affected by the fertilizer treatments was not affected by the treatments at both 60 DAP (Table 3) and at harvest (Table 4). The nutrient concentration of both nutrients with fertilized plots was equal compared to unfertilized plots.

Table 3. Soil phosphorus and potassium at 60 days after planting

Treat	Soil Phosphorus (mg kg^{-1})	Soil Potassium (mg kg^{-1})
T1 (P1K1)	184.3 a	31.5 a
T2 (P1K2)	155.1 a	22.9 a
T3 (P1K3)	120.4 a	19.2 a
T4 (P2K1)	135.1 a	27.6 a
T5 (P2K2)	136.0 a	18.0 a
T6 (P2K3)	127.5 a	14.6 a

Table 4. Mehlich-3 soil phosphorus and potassium at tomato harvest

Treat	Soil Phosphorus (mg kg^{-1})	Soil Potassium (mg kg^{-1})
T1 (P1K1)	158.0 a	24.4 a
T2 (P1K2)	148.2 a	16.8 a
T3 (P1K3)	139.0 a	29.1 a
T4 (P2K1)	136.1 a	22.4 a
T5 (P2K2)	139.7 a	12.2 a
T6 (P2K3)	140.7 a	17.8 a

Leaf tissue concentration of phosphorus and potassium at 30 days after planting was equal among all the treatments including unfertilized control.

Table 5. Leaf tissue phosphorus and potassium at 30 days after planting

Treat	Soil Phosphorus (mg kg^{-1})	Soil Potassium (mg kg^{-1})
T1 (P1K1)	0.43 a	3.3 a
T2 (P1K2)	0.46 a	3.7 a
T3 (P1K3)	0.47 a	3.5 a
T4 (P2K1)	0.45 a	3.2 a
T5 (P2K2)	0.51 a	3.5 a
T6 (P2K3)	0.49 a	3.4 a

Similar to the leaf tissue concentration at 30 DAP, the tissue content of both phosphorus and potassium was equal among all treatments at 60 DAP (Table 6). However, the tissue concentration of both phosphorus and potassium declined at 60 DAP. The decline can be attributed to the translocation of these nutrients from leaf tissues to the fruit. Because the soil was high in both of the nutrients, the nutrient concentration is soil was enough to meet the requirement of the crop. Hence, tissue nutrient content was not affected by the application of fertilizers.

Table 6. Leaf tissue phosphorus and potassium at 60 days after planting

Treat	Soil Phosphorus (mg kg^{-1})	Soil Potassium (mg kg^{-1})
T1 (P1K1)	0.25 a	1.8 a
T2 (P1K2)	0.24 a	2.2 a
T3 (P1K3)	0.23 a	2.0 a
T4 (P2K1)	0.26 a	2.2 a
T5 (P2K2)	0.23 a	1.7 a
T6 (P2K3)	0.26 a	2.1 a

Tomato yield was not affected by the fertilizer treatments applied (Table 7). High temperature and rainfall during harvesting resulted in cracking and rotting of the fruit which resulted significant loss in the yield of marketable tomatoes. Equal tomato yield from unfertilized control and fertilized treatments indicated that the fertilization is not necessary to achieve the maximum yield.

Table 7. Effects of fertilizer treatments on tomato yield

Treat	Tomato yield (lbs/acre)
T1 (P1K1)	6651.6 a
T2 (P1K2)	10599.1 a
T3 (P1K3)	11350.8 a
T4 (P2K1)	11955.1 a
T5 (P2K2)	10881.4 a
T6 (P2K3)	10015.2 a

Conclusion

Background soil test concentration of both phosphorus and potassium was high. Hence, no phosphorus and potassium was recommended. The treatments included unfertilized control and other treatments comprised of various rates of phosphorus and potassium. The yield of the tomato was not affected by the treatments applied which indicated that fertilizer application above IFAS/UF recommendation does not increase crop yield. Therefore, Mehlich-3 extractant for soil tests, interpretations and nutrient recommendations are valid and realistic. Tomato growers can potentially save money adopting IFAS recommendations while sustaining optimal yields.

Green beans

In order to further demonstrate the results above, a trial in farmer's field was initiated in Alachua County planted to Green beans (var. Prevail) on September 21st. The study location was determined after conducting background soil sampling.

Unfortunately, the fields were washed out due to two large rainfall events and so the study was abandoned.

Belle Glade location

Dr. Mabry McCray, Agronomist,
IFAS Everglades Research and Education Center, Belle Glade

Sugarcane Field Trials on Mineral Soils

Phosphorus Rate Trial

In sandland phosphorus (P) rate trials we have had fourteen individual crop years across six sites (Table 1). Phosphorus rates ranged from 0 to 150 lb P_2O_5/acre at Site 1 and from 0 to 125 lb P_2O_5/acre at Sites 2-6. There were recently completed harvest samples for Site 4 (second ratoon), Site 5 (second ratoon), and Site 6 (first ratoon) in November-December 2017. There was a significant linear sugarcane yield response to P fertilizer at Site 4 in the second ratoon crop. Although yields were relatively low in this crop because of the short regrowth period following a late harvest the previous season, relative sucrose yield was 76% for the zero P treatment in the second ratoon crop at Site 4. Relative sucrose yields of 83, 73, and 79% for the zero P treatment in the plant cane, first ratoon, and second ratoon crops at Site 1 indicate some yield response to P fertilizer at Site 1 also. These relative sucrose yields were calculated by dividing tons sugar/acre of the zero P treatment mean by the highest yielding treatment mean for each crop at each location.

There is not a clear relationship of preplant Mehlich 3-extractable soil P with relative sucrose yield at this point in the study (Figure 1). There has not been a significant yield response to P fertilizer at Site 6 even though initial Mehlich 3-extractable soil P was the lowest of the six locations. Other extractants are being evaluated and relationships of ammonium acetate-extractable soil P and water-extractable soil P with relative sucrose yield are shown in Figure 2 and 3, respectively. The results so far for ammonium acetate and water suggest that these have potential for a calibration of soil test P for sugarcane on mineral soils, but preplant values for these two extractants have not yet been completed for Site 6. Leaf nutrient analysis is also being completed and should be useful in evaluating crop response and P sufficiency. We have one more crop year at Site 6 and a new P trial was planted in September 2017.

Potassium Rate Trial

There have been significant responses in tons sugar/acre to potassium (K) fertilizer in three of five K trial sites in the sandland K rate study (Table 2). At Site 2, replications 1-3 were substantially different from replications 4-6 in terms of organic matter and extractable soil K, so the analysis of variance was done separately for these groups. The relationship between relative sucrose yield and acetic acid-extractable soil K shows potential for a soil test calibration (Figure 4), with acetic acid-extractable K values <40 g/m^3 including lower relative yields. Soil extractions have not been completed for Site 6 and so Site 6 is not included in Figure 4. Other soil extractants being evaluated for soil test K are Mehlich 3 and ammonium acetate. A new K rate trial was planted in September 2017 and there will be one more crop year at Site 6.

Table 1. Least squares means for tons sugar/acre for all crop years of the sandland P rate study.

P Rate	Site 1	Site 1	Site 1	Site 2	Site 2	Site 3	Site 4	Site 4	Site 4	Site 5	Site 5	Site 5	Site 6	Site 6
lb P_2O_5/ac	Plant	R1[a]	R2[a]	Plant	R1	Plant	Plant	R1	R2	Plant	R1	R2	Plant	R1
	--------------------Tons sugar/acre--------------------													
0	6.06b[b]	3.84a	3.78a	8.36a	6.73a	8.76a	8.76a	4.10a	2.02b	9.32a	6.16a	5.49a	9.47a	6.70a
19	6.53ab	4.23a	4.48a											
25				8.25a	6.38a	8.62a	8.78a	4.30a	2.16b	9.09a	5.96a	5.44a	9.34a	6.25a
38	6.87ab	4.38a	4.30a											
50				7.95a	6.21a	8.96a	8.27a	4.04a	2.25ab	9.00a	6.16a	5.34a	9.63a	6.57a
75	6.89ab	5.12a	4.76a	8.30a	7.15a	7.63a	8.36a	4.54a	2.27ab	9.15a	5.74a	5.04a	9.46a	6.05a
100				8.85a	6.36a	8.80a	8.97a	4.24a	2.33ab	8.86a	6.01a	5.62a	9.68a	6.64a
125				8.67a	6.67a	8.22a	8.33a	4.26a	2.65a	8.49a	6.12a	5.01a	9.46a	6.61a
150	7.34a	5.28a	4.13a											
P>F	0.124	0.110	0.499	0.768	0.264	0.627	0.486	0.372	0.034	0.504	0.666	0.225	0.971	0.482

[a] R1: first ratoon, R2: second ratoon

[b] Within columns, means for tons sugar/acre followed by the same letter are not significantly different according to Tukey-Kramer at $P \leq 0.10$.

Table 2. Least squares means for tons sugar/acre for all crop years of the sandland K rate study.

K Rate	Site 2	Site 2	Site 2	Site 2	Site 3	Site 3	Site 4	Site 4	Site 5	Site 5	Site 5	Site 6	Site 6
lb K_2O/ac	Plant	R1[a]	Plant	R1	Plant	R1	Plant	R1	Plant	R1	R2	Plant	R1
	Reps 1-3	Reps 1-3	Reps 4-6	Reps 4-6									
	--------------------Tons sugar/acre--------------------												
0	4.02b[b]	3.22b	7.89a	4.94b	7.04b	3.20a	8.32a	4.85a	7.24c	4.43b	4.02b	6.92d	5.49b
50	6.65a	6.66a	7.39a	5.38ab	7.66ab	4.71a	8.36a	4.80a	7.56bc	5.06ab	4.96ab	7.88bcd	6.68a
100	7.18a	5.90ab	8.04a	5.51ab	8.07ab	4.71a	8.69a	5.09a	8.07abc	5.29a	5.45a	8.66abc	6.71a
150	7.80a	6.03ab	7.64a	5.80ab	8.21ab	5.04a	8.05a	5.16a	8.17abc	5.67a	5.36a	8.89ab	6.82a
200	7.50a	5.16ab	7.93a	6.29ab	7.77ab	4.36a	8.28a	4.76a	8.19abc	5.57a	5.49a	8.05abc	6.26ab
250	7.60a	4.50ab	7.45a	5.30ab	8.42ab	4.73a	7.85a	5.19a	8.41ab	6.60a	5.13a	7.77cd	5.99ab
300	7.62a	6.20a	8.86a	6.20ab	8.00ab	4.49a	8.12a	5.01a	8.85a	5.53a	5.76a	9.07a	6.59a
$P>F$	<0.001	0.052	0.184	0.074	0.128	0.230	0.787	0.187	0.003	<0.001	0.002	<0.001	0.004

[a] R1: first ratoon; R2: second ratoon

[b] Within columns, means for tons sugar/acre followed by the same letter are not significantly different according to Tukey-Kramer at $P \le 0.10$.

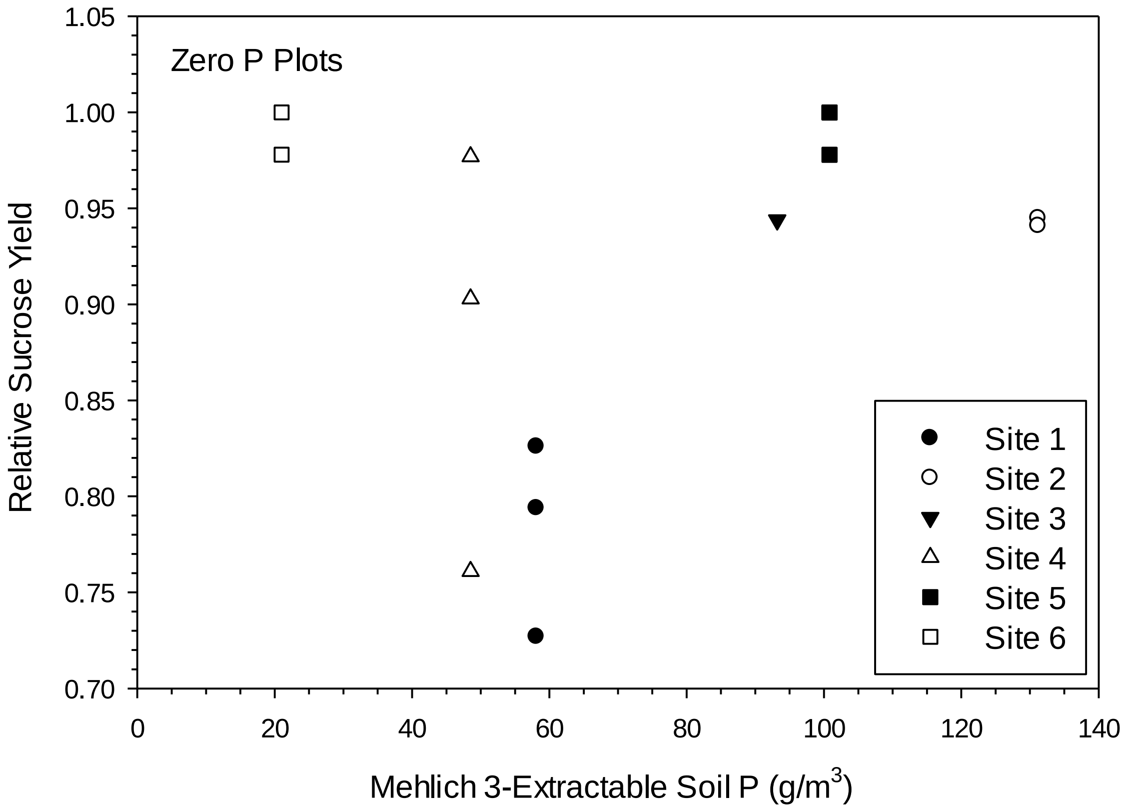


Figure 1. Relationship between relative sucrose yield and initial Mehlich 3-extractable soil P for the zero P treatment in the sandland phosphorus rate study.

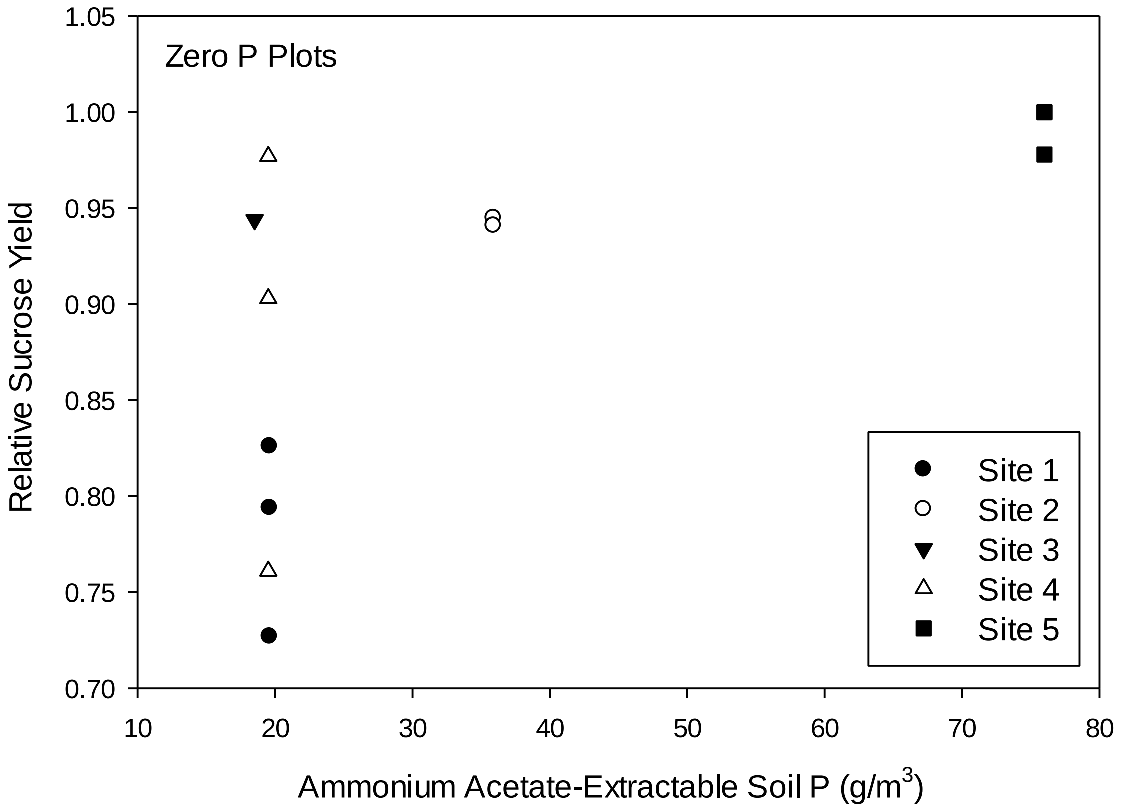


Figure 2. Relationship between relative sucrose yield and initial 1.0 *N* ammonium acetate-extractable soil P for the zero P treatment in the sandland phosphorus rate study.

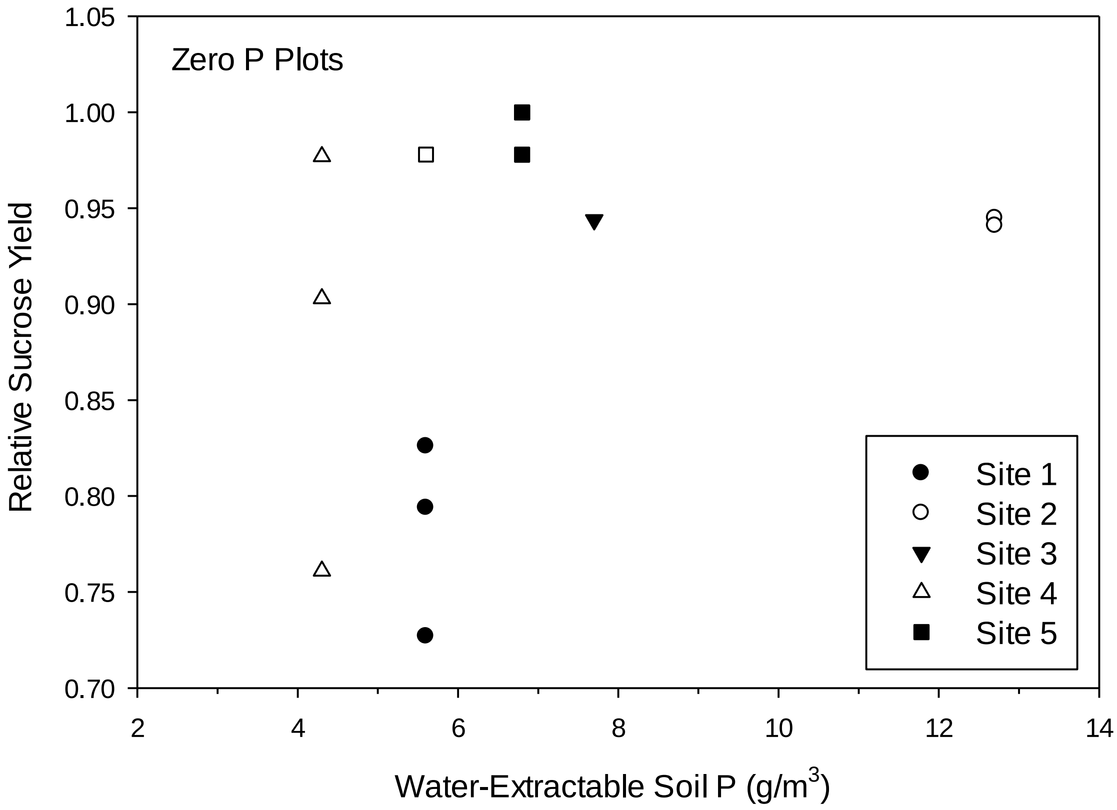


Figure 3. Relationship between relative sucrose yield and initial water-extractable soil P for the zero P treatment in the sandland phosphorus rate study.

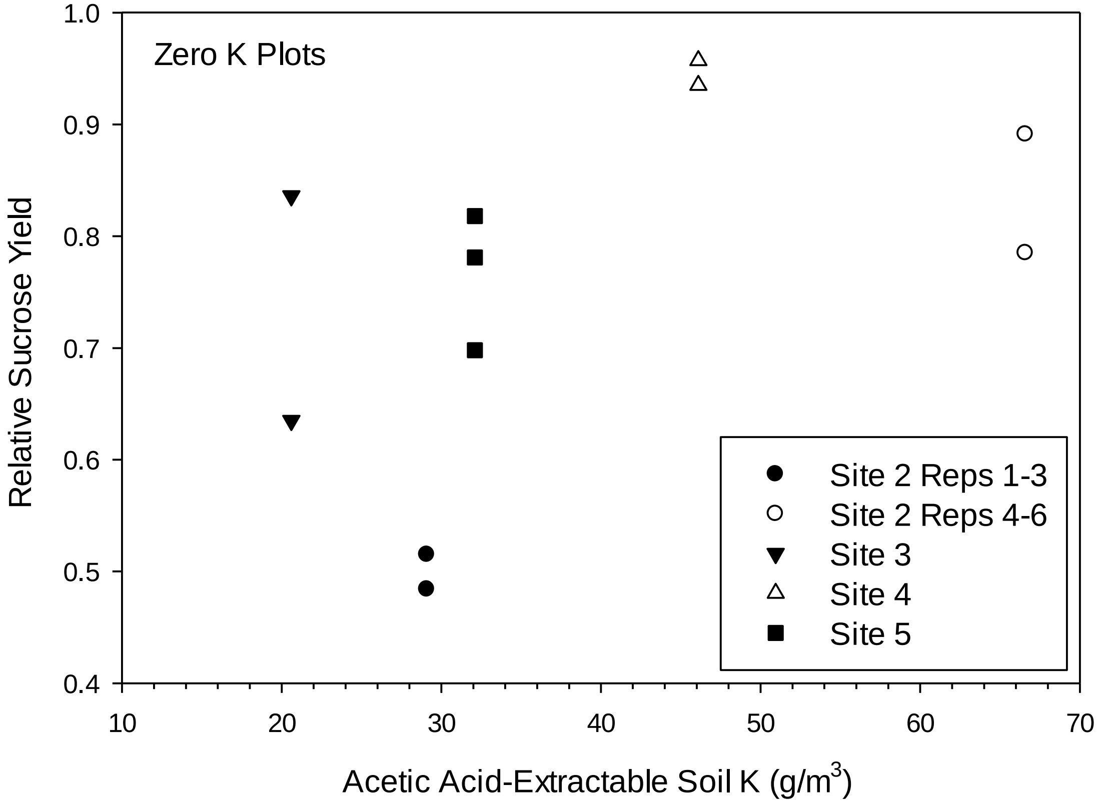


Figure 4. Relationship between relative sucrose yield and initial 0.5 *N* acetic acid-extractable soil K for the zero K treatment in the sandland potassium rate study.

Organic Soils, Belle Glade Location

Dr. Alan Wright, Assoc. Professor
Indian River Research & Education Center,
Ft. Pierce, FL

Iceberg Lettuce Report

Current soil test recommendations for iceberg or head lettuce are made by the Everglades Soil Testing Laboratory, University of Florida, at the Everglades Research & Education Center in Belle Glade, FL. Current soil test guidelines for muck soils use a water extraction procedure (Pw) to determine plant-available P concentrations in soils, then give a recommendation as to the amounts of P_2O_5 to add to soil to bring the plant-available P concentrations in soil to a desired concentration, which varies for different crops. For iceberg lettuce, the soil test Pw value for which no additional P fertilization is recommended is 27 lb P_2O_5/acre. Iceberg lettuce and romaine lettuce P fertilizer recommendations are listed separately in the guidelines, although recommendations are the same. Thus, there is a need to determine if in fact both iceberg and romaine lettuce require the same quantities of P fertilizer and can follow the same recommendation.

This experiment was designed to test a wide range of soil plant-available P concentrations, as measured using the standard Pw test (official method for vegetable crops used by the ESTL for muck soils) and comparing results with a Mehlich 3 extraction method recommended currently for sandy soils and muck soils growing sugarcane. Soil test values were then related to iceberg lettuce yield in a similar fashion as was reported for romaine lettuce in 2017 for this project.

The field experiment was arranged using a randomized block design on Dania soil series, with average soil pH of 7.2. Higher or lower soil pH values have been demonstrated to affect relationships between soil test extraction methods on muck soils, so this experiment represents sites only at a similar pH range. However, all lettuces are produced primarily in the northern Everglades Agricultural Area which consists mostly of Dania soil series, which is characterized by shallow soil conditions and pH values above 7.0. Thus, the site location used for this study is representative of soil conditions typically used for commercial lettuce production within the EAA. Each plot was 12 by 25 feet in length and consisted of 4 beds with 2 rows of lettuce per bed. Nitrogen, K, and micronutrients were applied at similar rates across treatments, but P as triple superphosphate was applied at variable rates to generate a wide range of soil test P values above the unfertilized control (background approximately 4 lb P_2O_5/ac). Soils were sampled before planting to determine amounts of P fertilizers needed, and again at harvest from 0-6 inch depths, with three cores collected in a plant row per plot and homogenized. Soil samples were then analyzed for plant-available P concentrations using the Pw and the Mehlich 3 test.

Soil Pw and Mehlich 3 extractable P concentrations showed a strong relationship at the lower range, when Pw was below 100 mg/kg and Mehlich 3 was below 350 mg/kg. Above these concentrations, the relationship of Pw to Mehlich 3 deteriorated somewhat. Mehlich 3 concentrations averaged 7 times higher than the Pw, as the more acidic nature of the Mehlich 3 extractant was able to capture P from more recalcitrant soil P forms than the water extractant. Overall, the relationship between Mehlich 3 and Pw best fit a linear model with r^2=0.77.

Relationships between soil extraction methods and iceberg lettuce yield produced similar results, with both soil tests being good predictors of crop response. Yield response to variable rate P application was linear from background soil P concentrations to 80 mg P/kg, then yields tended to plateau at soil P concentrations above 80 mg P/kg, indicating that there was minimal benefit of P fertilizers above this threshold. The yield response curve was betted fitted by a logarithmic equation with r^2 of 0.84.

The Mehlich 3 produced a similar response to the Pw test in terms of crop response, with a linear increase in iceberg lettuce yield with increasing Mehlich 3 P concentrations up to a threshold of approximately 300 mg P/kg. At Mehlich3 P concentrations above this threshold, there was minimal yield response to increasing soil P concentrations. Similar to the Pw test, iceberg yield fitted a logarithmic model best with an r^2 of 0.85. Yield response curves for the Pw test and the Mehlich 3 test produced similar r-squared values of 0.84 and 0.85, indicating that both tests were suitable for predicting yield response of iceberg lettuce.

Romaine lettuce yield response curve differed slightly from the iceberg lettuce curve in that romaine lettuce response to P enrichment was linear up to a threshold value of 60 mg P/kg for Pw and 250 mg P/kg for Mehlich3, then yield response plateaued above these threshold values. For iceberg lettuce, however, yield response was logarithmic for the entire yield response curve from background soil P concentrations up 171 and 612 mg P/kg for Pw and Mehlich 3, respectively. However, these results for iceberg lettuce were quite similar to those reported for romaine lettuce in 2017, indicating that both iceberg and romaine lettuce respond similarly to variable P fertilizer application rate, and that both lettuces should be listed under the same P fertilizer recommendation guidelines. Overall, Mehlich 3 performed just as well as the Pw test for predicting iceberg and romaine lettuce yield response to variable rate P fertilization.

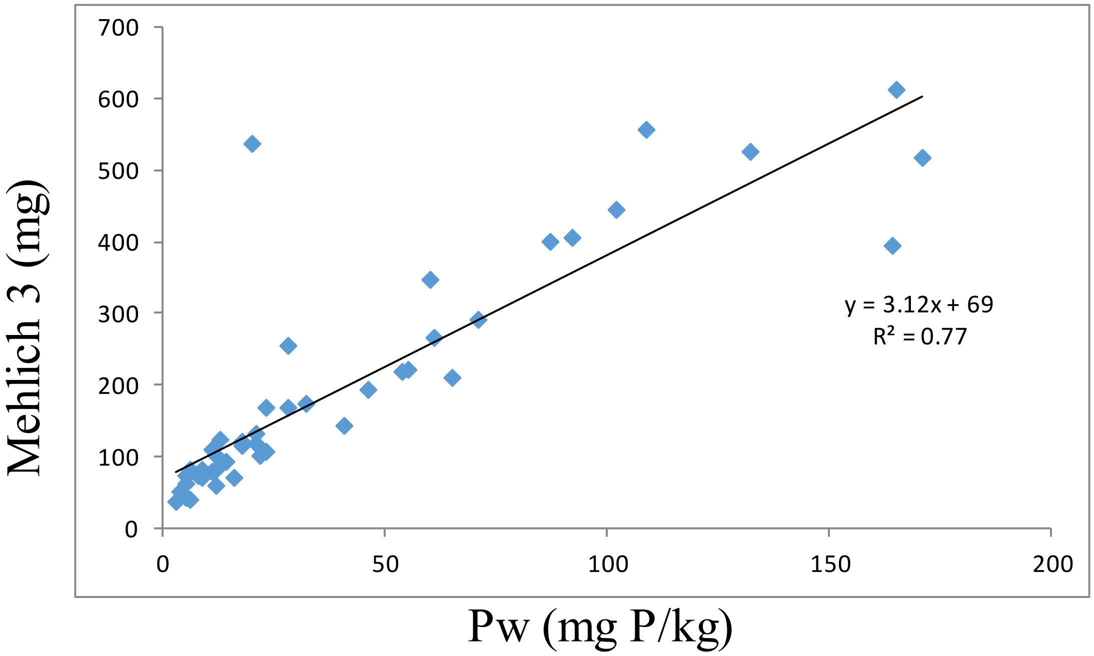


Figure 1. Comparison of plant-available P concentrations generated using the water extractant test (Pw) and the Mehlich 3 test for iceberg head lettuce grown on muck soils.

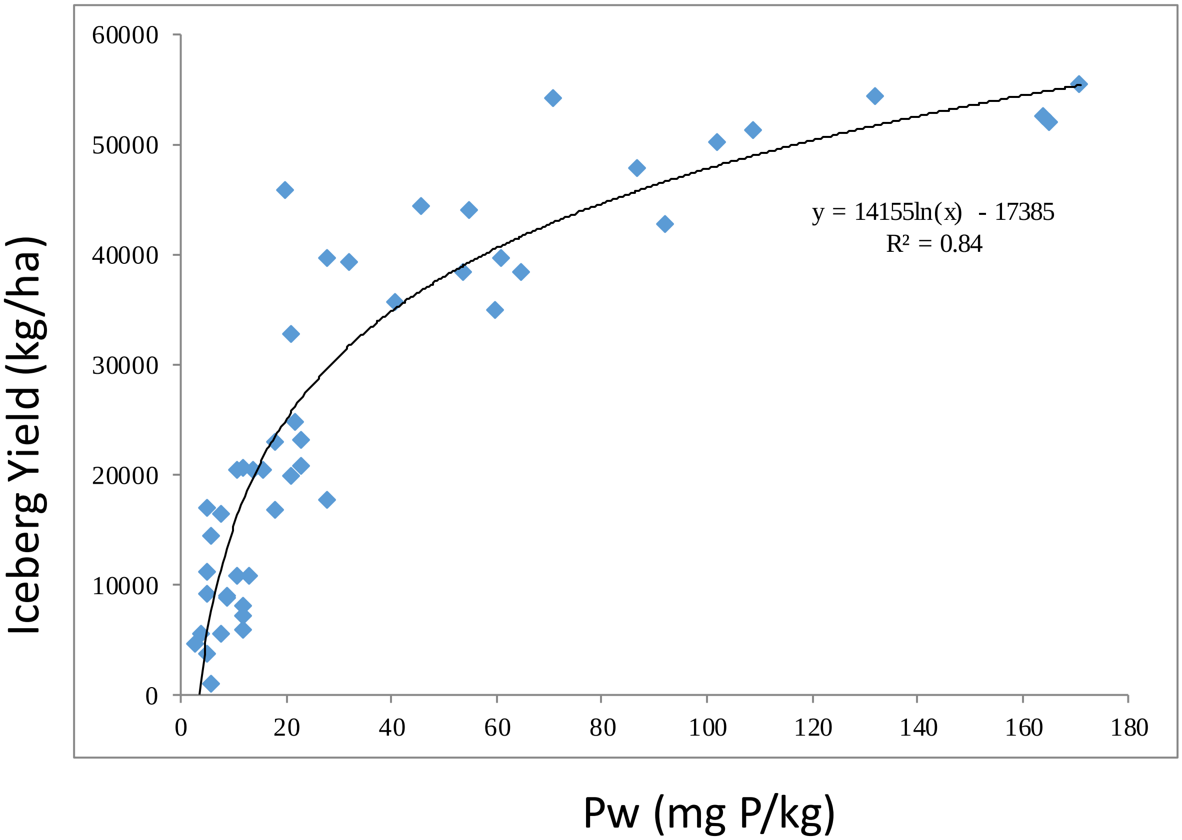


Figure 2. Relationship between water extractable P (Pw) concentrations at planting and iceberg lettuce yield.

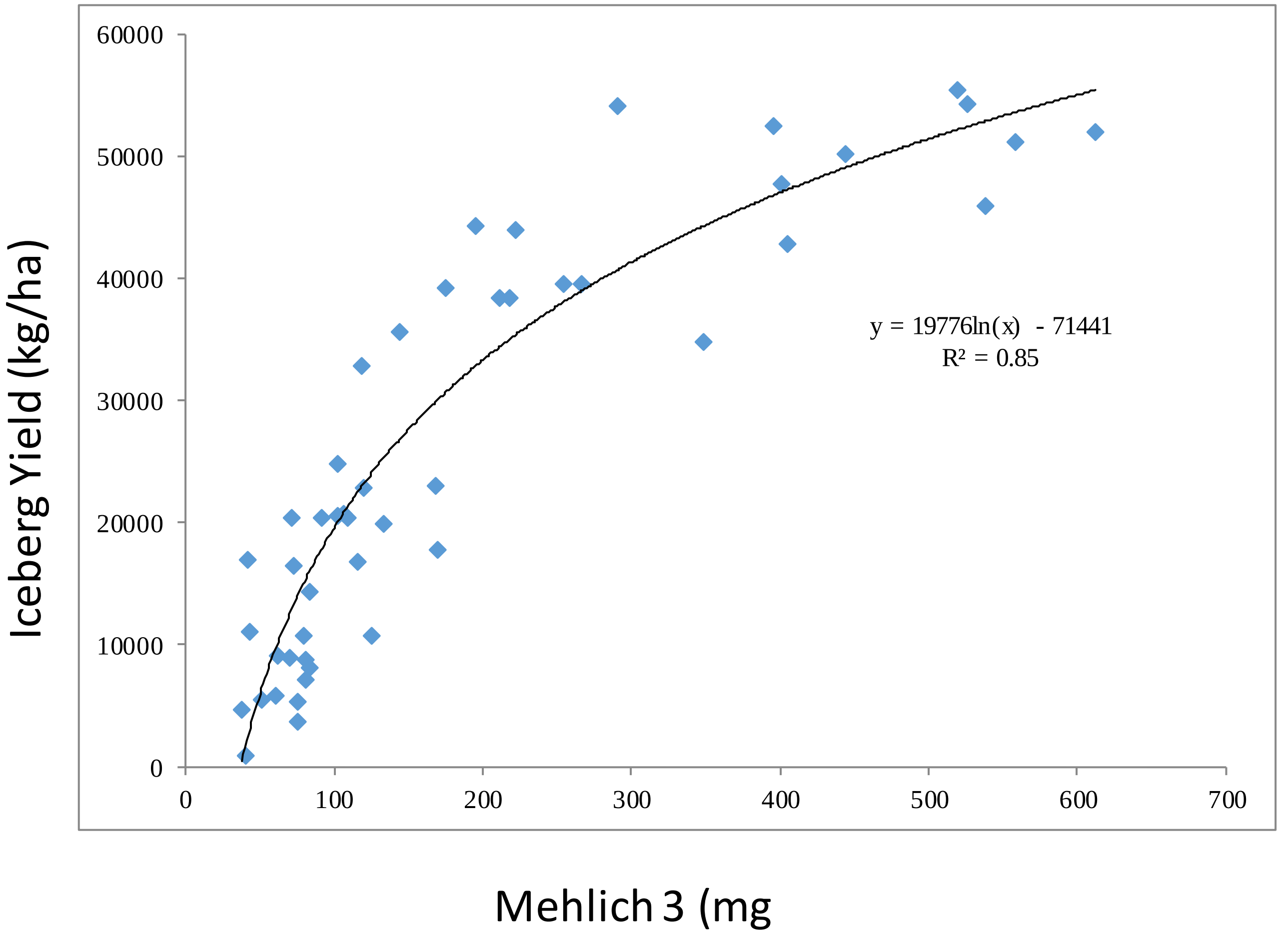


Figure 3. Relationship between Mehlich 3 extractable P concentrations at planting and iceberg lettuce yield.

Sweet Corn Report

Current soil test recommendations for sweet corn are made by the Everglades Soil Testing Laboratory, University of Florida, at the Everglades Research & Education Center in Belle Glade, FL. Current soil test guidelines for muck soils use a water extraction procedure (Pw) to determine plant-available P concentrations in soils, then give a recommendation as to the amounts of P_2O_5 to add to soil to bring the plant-available P concentrations in soil to a desired concentration, which varies for different crops. For sweet corn, the soil test Pw value for which no additional P fertilization is recommended is 14 lb P_2O_5/acre.

This experiment was designed to test a wide range of soil plant-available P concentrations, as measured using the standard Pw test (official method for vegetable crops used by the ESTL for muck soils) and comparing results with a Mehlich 3 extraction method recommended currently for sandy soils and muck soils growing sugarcane. Soil test values were then related to sweet corn yield in a similar fashion as has been reported for snap beans, and romaine and iceberg lettuce, for this project.

The field experiment was arranged using a randomized block design on Dania soil series, with average soil pH of 7.3. Higher or lower soil pH values have been demonstrated to affect relationships between soil test extraction methods on muck soils, so this experiment represents sites only at a similar pH range. However, most sweet corn production in the EAA is situated primarily in the northern Everglades Agricultural Area which consists mostly of Dania soil series, which is characterized by shallow soil conditions and pH values above 7.0. Thus, the site location used for this study is representative of soil conditions typically used for commercial corn production within the EAA. Each plot was 12 by 25 feet in length and consisted of 4 rows of corn per plot. Nitrogen, K, and micronutrients were applied at similar rates across treatments, but P as triple superphosphate was applied at variable rates to generate a wide range of soil test P values above the unfertilized control (background approximately 6 lb P_2O_5/ac). Soils were sampled from 0-6 inch depths, with three cores collected in a plant row per plot and homogenized. Soil samples were then analyzed for plant-available P concentrations using the Pw and the Mehlich 3 test.

Soil Pw and Mehlich 3 extractable P concentrations generally did not show a strong relationship across the entire range, with only an r^2 of 0.48. Relationships between Pw and Mehlich 3 showed much higher correlation for other vegetation crops than observed for sweet corn. Mehlich 3 concentrations averaged 12 times higher than the Pw for sweet corn, as the more acidic nature of the Mehlich 3 extractant was able to capture P from more recalcitrant soil P forms than the water extractant.

Relationships between soil extraction methods and sweet corn yield produced similar results, with neither soil test being a particularly good predictor of crop response for this growing season. Yield response to variable rate P application was variable potentially due to field conditions and variable seed germination rate. The yield response curve was best fitted by a logarithmic equation with r^2 of 0.50 for Mehlich 3 and 0.37 for Pw.

Romaine lettuce, iceberg lettuce, and snap bean (2016 and 2017 projects) all showed a good response to variable rate P evaluation, and indicated that Mehlich 3 performed as suitably as the Pw test for predicting crop response. However, for this particular growing season, sweet corn yield response was not accurately predicted by soil P testing. However, Mehlich 3 performed slightly better than the Pw test for sweet corn. Further studies are warranted across multiple growing seasons to capture the variability associated with field testing.

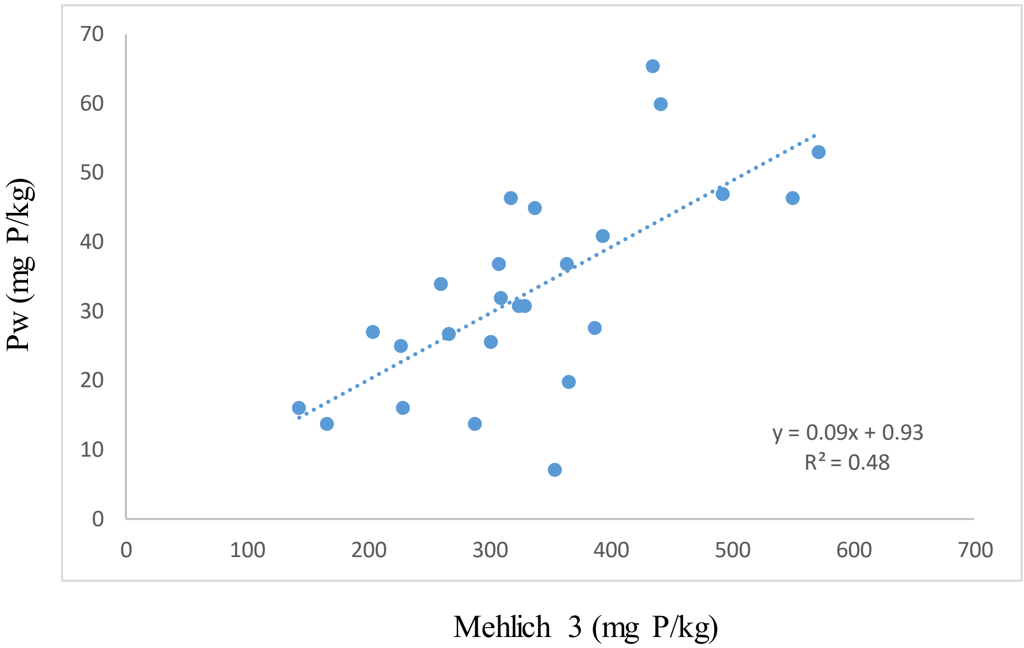


Figure 4. Comparison of plant-available P concentrations generated using the water extractant test (Pw) and the Mehlich 3 test for sweet corn grown on muck soils.

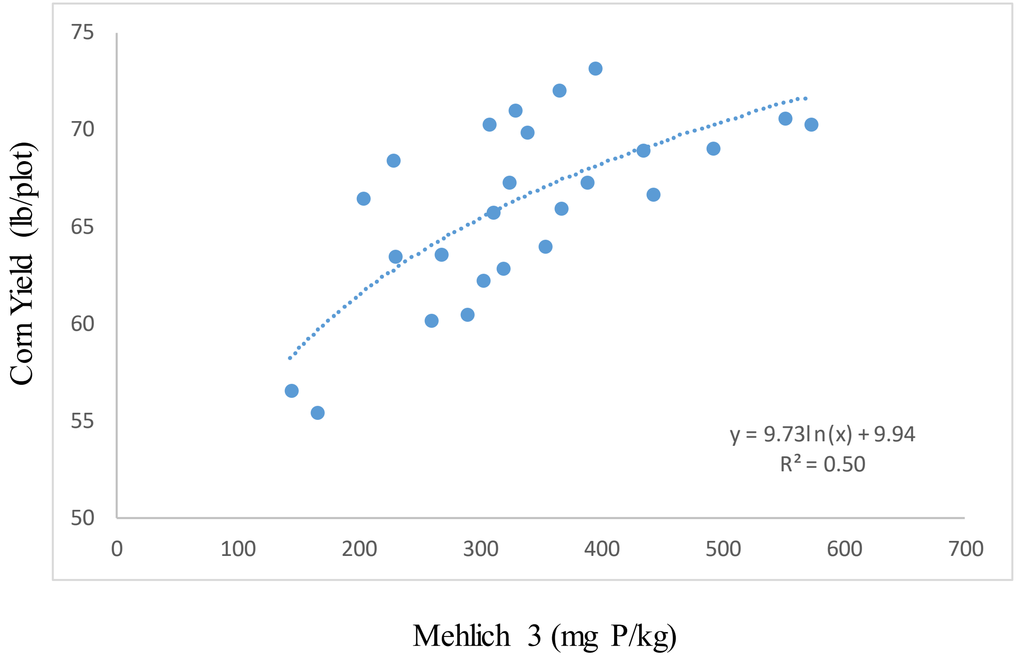


Figure 5. Relationship between Mehlich 3 extractable P concentrations at planting and sweet corn yield.

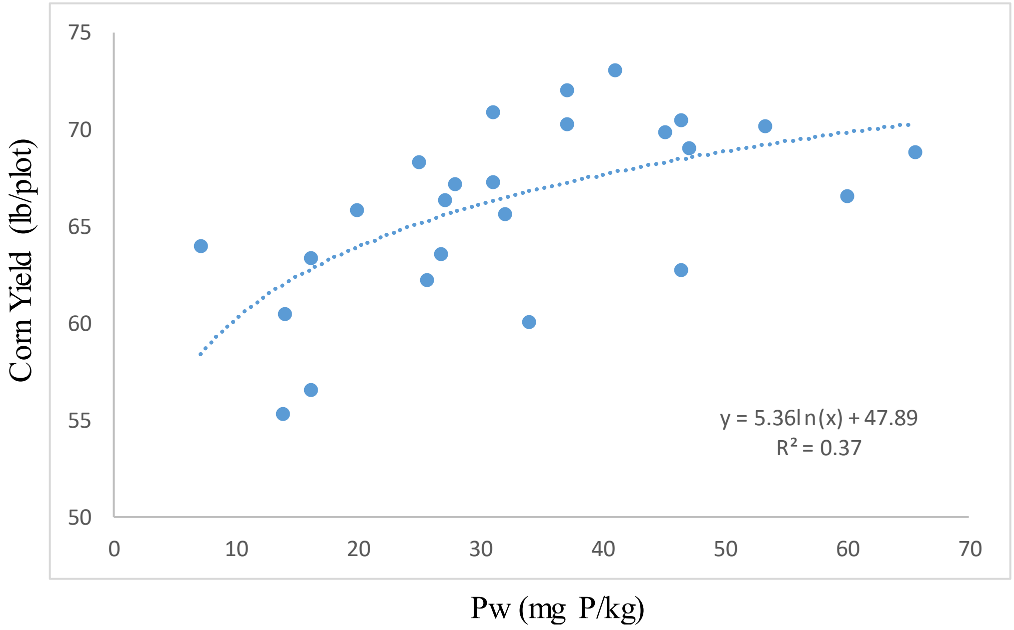


Figure 6. Relationship between water extractable P (Pw) concentrations at planting and sweet corn yield.

Homestead Site

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Experiment 1. Comparison of Extractants for Calibrating Phosphorus Application Rates in a Calcareous Soil

In Florida, the STP interpretations have been established for vegetables grown on acid-mineral soils using Mehlich-3 (Mylavarapu, et al., 2014). In calcareous soils, however, AB-DTPA was adopted and 10 mg P kg^{-1} was proposed to be the threshold for vegetable production without calibrated interpretations (Li et al., 2000). Currently, the STP concentrations in cultivated areas are mostly above 10 mg P kg^{-1} due to long term intensive P fertilization, indicating the limited applicability of AB-DTPA extractant. Because no soil test calibration has been performed, the STP interpretations and P recommendations are not available. Therefore, the objectives of this study were to: (i) compare three extactants, Mehlich-3, AB-DTPA, and Olsen, in estimating P availability with different P application rates; (ii) establish preliminary numerical STP criteria; and (iii) calibrate P requirement for tomato production in a calcareous soil.

The experiment was conducted on the research farm at University of Florida (UF)/Tropical Research and Education Center, Homestead, FL during the winter seasons of two years. The field (25° 30’ 47” N / 80° 30’ 3” W), which was fallow and goosegrass (*Eleusine indica* L. Gaertn) was the primary species growing there over the last ten years, was plowed and the grasses were incorporated into the soil. Sorghum-sudangrass (*Sorghum bicolor* × *S. bicolor var. sudanese*) was planted for 1 mo and the aboveground portions were manually removed from the field with the intention to reduce spatial variation of nutrient levels in soil. Basic soil properties before applying fertilizers in the the year one season were: gravel (> 2 mm), 632 g kg^{-1}; clay, 31 g kg^{-1}; silt, 49 g kg^{-1}; sand, 288 g kg^{-1}; pH, 7.8; electrical conductivity (EC), 248.2 µS cm^{-1}; carbonate concentration, 379.3 g kg^{-1}; organic matter, 56.9 g kg^{-1}; NO_3-N, 22.3 mg kg^{-1}; NH_4-N, 7.2 mg kg^{-1}; total P, 1473 mg kg^{-1}; total K, 1422.7 mg kg^{-1}; and AB-DTPA extractable P, 14.7 mg kg^{-1}; K, 81.5 mg kg^{-1}; Fe, 6.3 mg kg^{-1}; Zn, 6.7 mg kg^{-1}; and Mn, 11.1 mg kg^{-1}.

From the end of the season in the year one to the beginning of the season in the year two (24 Mar. to 15 Oct.), the field was left fallow without polyethylene mulch. Treatments were arranged in a randomized complete block design with three replications and all the treatments were in the same locations during the two seasons. Each plot was 9.1 m long and 5.5 m wide (included three adjacent beds). Beds were formed 183 cm center to center, 20 cm high, and 91 cm wide across the top. Phosphorus application rates included 0, 29, 49, 78, 98, and 118 kg P ha^{-1}. Total season nitrogen (N) and K were applied at the same rates for all treatments with 224 kg N ha^{-1} N and 149 kg K ha^{-1}, respectively. All the P, 56 kg N ha^{-1}, and 56 kg K ha^{-1} were applied as preplant dry fertilizers. The residual N and K were supplied through drip fertigation from the first flowering to the first harvest. Fertilizer application rates were selected according to the recommendations for tomato grown on acid-mineral soils in Florida as well as a previous pot study using the same calcareous soils with the present study (Zhu et al., 2016). Preplant dry fertilizers were banded 8 cm below and 15 cm to each side of the bed center. After preplant fertilizer application, beds were covered with polyethylene mulch (Guardian Standard white on black; Guardian AgroPlastics Inc., Florence, SC). Tomato seedlings (cultivar Ridgerunner; Syngenta, Greensboro, NC) were transplanted in the bed center 8 d after preplant fertilization (DAPF) in both years. Plant spacing was 46 cm, resulting in a population of 11,960 plant ha^{-1}. Pest control and irrigation management were conducted following UF/Institute of Food and Agricultural Sciences recommendations (Freeman et al., 2014a).

Soil samples were collected at 40, 70, 105, and 145 d after preplant fertilization (DAPF) in the year one and 30, 60, 90, and 120 DAPF in the year two and extracted by Mehlich-3 (following the procedure from Mehlich, 1984), AB-DTPA (following the procedure from Soltanpour and Schwab, 1977), Olsen (following the procedure from Olsen et al., 1954), and water (following the procedure from Korndorfer et al., 1995). Leachate samples were collected from the plots with P rates of 0, 29, 78, and 118 kg P ha^{-1} at 39, 74, 94, and 138 DAPF in the year one and 30, 63, 93, and 122 DAPF in the year two. The leachate were captured by gravitational lysimeters (28-cm internal diameter by 61-cm depth), which were buried under the soil surface layer at a depth of 20 cm. The P concentration in the extract and the DRP concentration in the leachate were analyzed by the ascorbic acid-Mo blue method with spectrophotometer (DU 640; Beckman Instruments Inc., Fullerton, CA) (Murphy and Riley, 1962). The DRP load was computed from multiplying leachate DRP concentration by the volume of leachate.

One entire plant in each plot was collected at 38 DAPF in both seasons, and the leaf, stem, and root parts were separated. The P uptake was calculated from multiplying dry weight by the P concentration in each part, which was analyzed by inductively coupled plasma-optical emission spectroscopy (Optima 7000 DV ICP-OES; PerkinElmer Inc., Waltham, MA). Tomato fruits were harvested at 119, 133, and 146 DAPF in the year one and 96, 110, and 124 DAPF in the year two as the first, second, and third harvests, respectively. Relative yield was calculated from dividing the actual yield by the maximum yield in each season.

Statistical analyses were carried out by SAS program (Version 9.2; SAS Institute Inc., NC). The GLM procedure and Duncan's Multiple Range Test were used to separate the means of STP and marketable yield among different P rates or sampling dates. Simple linear and split-line models were used to evaluate the correlations among STP and the relationship between STP and leachate DRP. To correlate with STP, the leachate DRP were collected 24-39 d later than the related soil sampling dates, while at 39 DAPF in the year one and 30 DAPF in the year two, only the leachate DRP from the treatment without P fertilization were included. The better fit model was selected based on $P < 0.05$ and higher coefficient of determination (r^2). The acceptable standard error for the change point was 40% or less in the split-line model (McDowell et al., 2001).

Two approaches were adopted to calibrate P rates. A multiple regression model (Relative yield = a + b×STP + c×P rate + d×STP^2 + e×P rate^2 + STP×P rate) was used in the first approach (Slaton et al., 2009; Zhu et al., 2017). In the second approach, linear, quadratic, linear-plateau, and quadratic-plateau regression models were performed to analyze the relationships between tomato relative yield and soil available P at 30 or 40 DAPF and between soil available P and P rate. Soil available P in each plot was calculated by adding STP at 30 or 40 DAPF with plant P uptake at 38 DAPF, in which the unit of kg ha^{-1} was transformed to mg kg^{-1} using 1.2 g cm^{-3} soil bulk density and 20-cm depth. Potential outliers were detected by the Studentized Deleted Residuals (< -3 and > 3). In both approaches, 50, 75, and 90% relative yield were set as the critical yield level to calculate STP threshold and required P rates (Savoy, 2013; Zhu et al., 2017).

Results

In the year one at 105 and 145 DAPF, Mehlich-3-P was significantly affected by P rates and the rate of 118 kg P ha^{-1} resulted in significantly higher Mehlich-3-P concentration than 0 and 78 kg P ha^{-1} (Table 1). Both AB-DTPA-P and Olsen-P were significantly affected by P rates at 70 and 105 DAPF in the year one. With P rate of 118 kg P ha^{-1}, Mehlich-3-P and Olsen-P were significantly affected by sampling dates and the highest concentration occurred at 105 DAPF in the year one. In the year two, all STP concentrations were not significantly affected by P rates at 0 DAPF, but at 30 DAPF, P rate of 78 and 118 kg P ha^{-1} resulted in significantly higher STP than 0 and 29 kg P ha^{-1} (Table 2). With P rate of 118 kg P ha^{-1}, Mehlich-3-P and AB-DTPA-P at 30, 60, and 90 DAPF were significantly higher than 0 and 120 DAPF, whereas Olsen-P at 90 DAPF was significantly higher than other sampling dates in the year two. Initial STP concentrations (at 0 DAPF) in the year two averaging from all P rates increased by 40% for Mehlich-3-P and decreased by 13 and 10% for AB-DTPA-P and Olsen-P, respectively, compared with those values in the year one. Without P fertilization, all STP concentrations were unaffected during all the sampling dates of the year and two.

The amounts of STP extracted by Mehlich-3, AB-DTPA, and Olsen were significantly correlated (Fig. 1). The highest correlation was observed between Mehlich-3-P and Olsen-P and predicted by a split-line model. When Mehlich-3-P was higher than 99 mg P kg^{-1}, the slope of the correlation line significantly decreased from 2.1 to 0.45. Similar correlation occurred between Mehlich-3-P and AB-DTPA-P. Nonetheless, linear relationship was found between AB-DTPA-P and Olsen-P. Significant responses of water-P and leachate DRP to the STP concentrations were detected for all the three extractants (Fig. 2 and 3). The relationship between water-P and Mehlich-3-P was described by a split-line model (Fig. 2). A change point of 88 mg P kg^{-1} of Mehlich-3-P with a standard error of 3.7 was predicted. The split-line model using AB-DTPA-P had the lowest r^2 and could not yield a reasonable change point. However, a change point of 26 mg P kg^{-1} with a standard error of 3.1 was predicted from the relationship between water-P and Olsen-P. In the correlations with leachate DRP, the highest r^2 was observed using Mehlich-3-P (Fig. 3). A split-line model with a change point of 104 mg P kg^{-1} predicted the response of leachate DRP to Mehlich-3-P, whereas simple linear models predicted the responses to AB-

DTPA-P and Olsen-P. The threshold of DRP load leached from one winter tomato season was calculated as 58 g P ha^{-1} using the concentration threshold of 0.015 mg L^{-1} and the mean leaching volume of 23.7 L from the two seasons. When Mehlich-3-P concentration was 104 mg P kg^{-1}, the leached DRP was predicted at 26 g P ha^{-1}, which was lower than the threshold value. In the simple linear models, the x-intercepts of 7 and 10 mg P kg^{-1} were assumed to be the change points for AB-DTPA-P and Olsen-P, respectively.

Tomato marketable yields of the first harvest (FH) accounted for 47-66% and 13-54% of the total season harvest (TSH) yields in the year one and two, respectively (Table 3). In the year one, P rates at and above 78 kg P ha^{-1} resulted in significantly higher FH marketable yields than the rates below 49 kg P ha^{-1}. However, no significant differences were found in the marketable yields of the first and second combined harvest (FSH) and TSH in the year one. Significantly higher marketable yields were observed in both FH and FSH with P rates at and above 49 kg P ha^{-1} in the year two. Phosphorus rate of 78 kg P ha^{-1} resulted in the highest marketable yield in TSH of the year two. The marketable yields from FH in the year one and FSH in the year two were used to calculate relative yield in each season. The three multiple regression models were significant (Table 4; Fig. 4). These models predicted that 50% relative yield would be produced at 0 kg P ha^{-1} and 42, 13, and 19 mg P kg^{-1} of Mehlich-3-P, AB-DTPA-P, and Olsen-P, respectively. Mehlich-3-P and Olsen-P were 76 and 24 mg P kg^{-1}, respectively, when 75% relative yield was predicted without P fertilization. The 90% relative yield was predicted without P fertilization when Mehlich-3-P and Olsen-P were 89 and 26 mg P kg^{-1}, respectively. The model using AB-DTPA-P could not predict relative yield at or higher than 75% with P rate of 0 kg P ha^{-1}. Phosphorus rates of 138 and 52 kg P ha^{-1} were required to produce 90% relative yield for soils with 42 and 76 mg P kg^{-1} of Mehlich-3-P, respectively. The required P rates were 176 and 60 kg P ha^{-1} to produce 90% relative yield when Olsen-P were 19 and 24 mg P kg^{-1}, respectively, while 136 kg P ha^{-1} were predicted for soils having 13 mg P kg^{-1} of AB-DTPA-P.

The relationships between relative yield and soil available P were predicted by linear-plateau models using Mehlich-3-P and AB-DTPA-P (Fig. 5A and 5B). Calculated from the linear equations, 50 and 75% relative yield was predicted with 18 and 77 mg P kg^{-1} of Mehlich-3-P and 8 and 21 mg P kg^{-1} of AB-DTPA-P, respectively. Quadratic model described the response of relative yield to soil available P using Olsen-P and 50 and 75% relative yield were predicted when Olsen-P were 13 and 31 mg P kg^{-1}, respectively (Fig. 5C). The model using AB-DTPA-P could not predict tomato relative yield higher than 84% (plateau), but 90% relative yield was predicted with 113 and 49 mg P kg^{-1} of Mehlich-3-P and Olsen-P, respectively. In the relationships between soil available P and P rate, there were 3, 6, and 4 outliers detected and omitted for Mehlich-3-P, AB-DTPA-P, and Olsen-P, respectively (Fig. 6). All the responses of soil available P to P rate were predicted by quadratic models. Calculated from the quadratic equations, 54 and 49 kg P ha^{-1} of P were required to increase Mehlich-3-P from 77 to 113 mg P kg^{-1} and increase Olsen-P from 31 to 49 mg P kg^{-1}, respectively. Adopting the P index threshold of 150, when Mehlich-3-P concentrations were 42 and 77 mg P kg^{-1}, P rate should not exceed 112 and 95 kg P ha^{-1}, respectively (Table 5).

Discussion

Correlations among soil test phosphorus

In the present study, there were significant correlations among Mehlich-3-P, AB-DTPA-P, and Olsen-P. Similar results were observed by previous researches in calcareous soils (Ebeling et al., 2008; Ige et al., 2006; Pizzeghello et al., 2016; Zhu et al., 2016). The amounts of P extracted by Mehlich-3 were higher than the amounts extracted by AB-DTPA and Olsen, demonstrating that the hydrogen ion (H^+) plus F^- in Mehlich-3 were more effective in releasing P than HCO_3^- (Elrashidi et al., 2001). Furthermore, the efficiency of P extraction by HCO_3^- decreased with increasing P rates as indicated by Castro and Torrent (1995). Even though the same mechanism was followed to extract P by AB-DTPA and Olsen, the correlation between Mehlich-3-P and Olsen-P was higher than those between Mehlich-3-P and AB-DTPA-P and between AB-DTPA-P and Olsen-P. This result was probably attributed to the low solution to soil ratio (2:1) in the AB-DTPA extraction procedure.

In the relationship between Mehlich-3-P and Olsen-P, the slope of the correlation line significantly declined when Mehlich-3-P was higher than 99 mg P kg^{-1}. Nevertheless, simple linear relationship was found in previous studies with the exception of Kumaragamage et al. (2007), which showed the slope of the correlation line decreased from 2.3 to 1.6 when the range of Olsen-P concentrations expanded from 7-100 to 7-352 mg P kg^{-1}. The decreased slope was probably attributed to the reduced activity of H^+ and F^- through neutralization and precipitation, respectively. Differently from the present study, the simple linear relationship between Mehlich-3-P and Olsen-P occurred in soils with either less than 195 g kg^{-1} of carbonate content (Ebeling et al., 2008; Mallarino, 1997; Pizzeghello et al., 2016; Sen Tran et al., 1990) or lower than 40 mg P kg^{-1} of Mehlich-3-P (Iatrou et al., 2014). Thus, both the $CaCO_3$ and P contents should be taken into consideration when determining the relationship between P extractants in calcareous soils.

Soil test phosphorus threshold

From the agronomic perspective, the concentration of STP extracted by an effective extractant should be sufficiently correlated with crop response. Havlin et al. (2005) showed the crop response to soil P nutrition usually occurred at early plant growth stages. Additionally, the extra-large and large tomato fruits, which brought higher returns to growers than medium fruits, were mainly from the first and second harvest. As a result, the significantly affected tomato marketable yields at FH or FSH were selected to regress against STP. In the year two, the tomato yields of FSH rather than FH were used because of the relatively low proportion (13-54%) of FH in TSH yields. Ussiri et al. (1998) found AB-DTPA-P obtained higher correlation with corn (*Zea mays* L.) relative yields than Mehlich-3-P in soils with pH ranged from 4.8 to 7.7. In this study, the r^2 of the multiple regression models using Olsen-P and AB-DTPA-P were slightly higher than Mehlich-3-P. Nonetheless, all the three models were significant. In the other calibration approach, the responses of tomato relative yield to soil available P at early plant growth stage were also significant using the three extractants. The threshold (producing 90% relative yield) for AB-DTPA-P could not be predicted by either calibration approach. Combining the two approaches together, the medium rating scales of Mehlich-3-P and Olsen-P were identified from 77 to 113 and 31 to 49 mg P kg^{-1}, respectively.

When correlating with water-P, Mehlich-3-P and Olsen-P resulted in similar r^2 in the split-line models, which was consistent with the observations from Pizzeghello et al. (2016). Meanwhile, the split-line model using Mehlich-3-P explained the highest variability (66%) of leachate DRP. The change points were predicted to be 88-104 and 10-26 mg P kg^{-1} using Mehlich-3-P and Olsen-P, respectively. In calcareous soils, the change points of 100 and 40-60 mg P kg^{-1} were previously reported for Mehlich-3-P and Olsen-P, respectively (Bai et al., 2013; Ige et al., 2006; Pizzeghello et al., 2016). The different results might be due to different P sorption capacities of the soils as revealed by Hesketh and Brookes (2000). In this study, the change points of Olsen-P were below the medium rating scale for tomato production, which indicated that maintaining STP concentrations lower than the change points would not meet crop requirement. Nevertheless, 104 mg P kg^{-1} of Mehlich-3-P could be considered the threshold according to crop response and the environmental risk assessment. This threshold was higher than the related value of 45 mg P kg^{-1} in acid-mineral soils in Florida (Freeman et al., 2014), which might be attributed to the higher P fixation effect in the studied calcareous soils.

Phosphorus application rate recommendation

Based on the two calibration approaches, the very low STP levels were predicted lower than 42, 13, and 19 mg P kg^{-1} of Mehlich-3-P, AB-DTPA-P, and Olsen-P, respectively. At those critical concentrations, the required P rate using Olsen-P was 38-40 kg P ha^{-1} higher than the other two extractants. The recommended P rate was only 73 kg P ha^{-1} for tomato production on acid-mineral soils with low STP level in Florida (Freeman et al., 2014). In addition, Zhang et al. (2007) recommended 55 kg P ha^{-1} for tomato production in calcareous soils with lower than 50 mg P kg^{-1} of Olsen-P. Thus, the proposed P rate of 176 kg P ha^{-1} using Olsen-P seemed to be unreasonable. Lower and similar P rates were predicted from the multiple regression models for the very low levels of Mehlich-3-P and AB-DTPA-P. However, the rate of 138 kg P ha^{-1} using Mehlich-3-P was still higher than the maximum input (112 kg P ha^{-1}) according to the P index threshold. As a consequence, 112 kg P ha^{-1} was selected as the recommendation when Mehlich-3-P was 42 mg P kg^{-1}. At the medium STP level, the required P rate using Mehlich-3-P was predicted less than 54 kg P ha^{-1}, which were similar with the proposed amount using Olsen-P and lower than the ceiling amount calculated from P index.

Conclusions

There were significant correlations among the STP extracted by the three extractants. The correlation between Mehlich-3-P and Olsen-P was closer than that between AB-DTPA-P and Olsen-P. Very low STP levels were predicted below 42, 13, and 19 mg P kg^{-1} by the multiple regression models using Mehlich-3-P, AB-DTPA-P, and Olsen-P, respectively. The threshold of Mehlich-3-P was estimated 104 mg P kg^{-1}, whereas none of the regression models could predict the threshold of AB-DTPA-P. The required P amounts were predicted from 54 to 112 kg P ha^{-1} when Mehlich-3-P ranged from 77 to 42 mg P kg^{-1}. Neither calibration approaches using Olsen-P could propose the practical P rate for the low STP rating scale. Therefore, Mehlich-3 can be considered the most effective extractant to assess P availability and calibrate P rates in calcareous soils.

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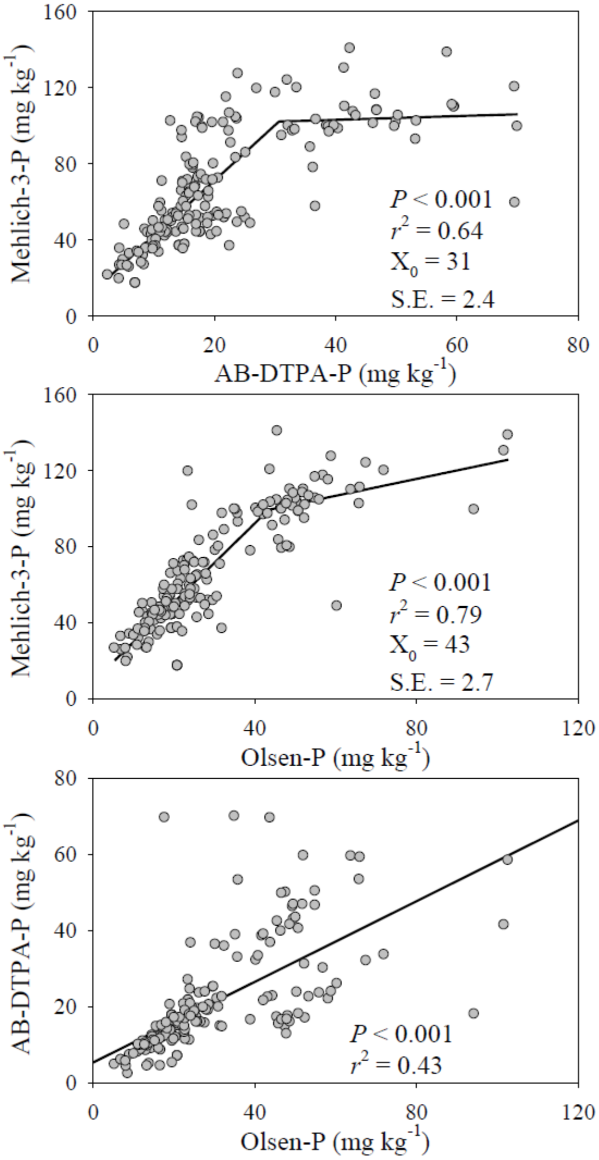

Figure 1. Correlation of soil test P concentrations extracted by Mehlich-3, AB-DTPA, and Olsen. Data points were the combination of the two tomato growing seasons. X_0, change point of soil test P; S.E., standard error for the change point.

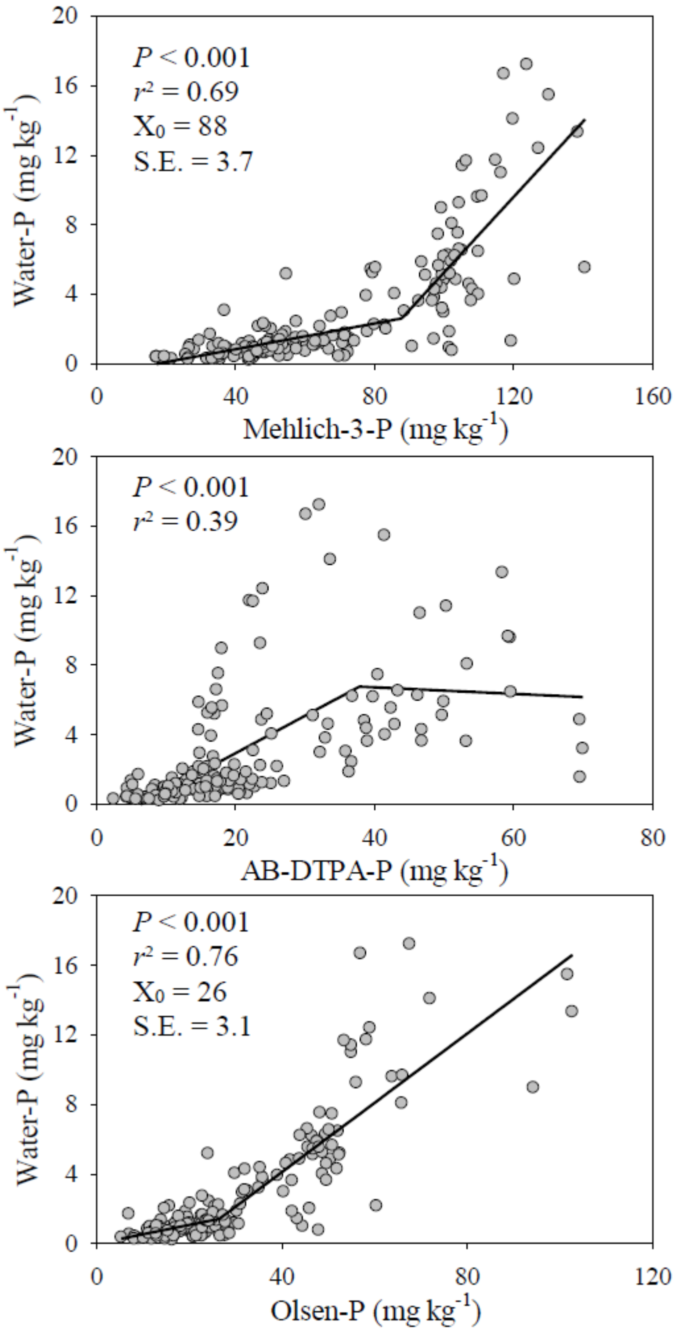

Figure 2. Relationships between soil test P extracted by Mehlich-3, AB-DTPA, and Olsen and soil solution P extracted by water. Data points were the combination of the two tomato growing seasons. X_0, change point of soil test P; S.E., standard error for the change point.

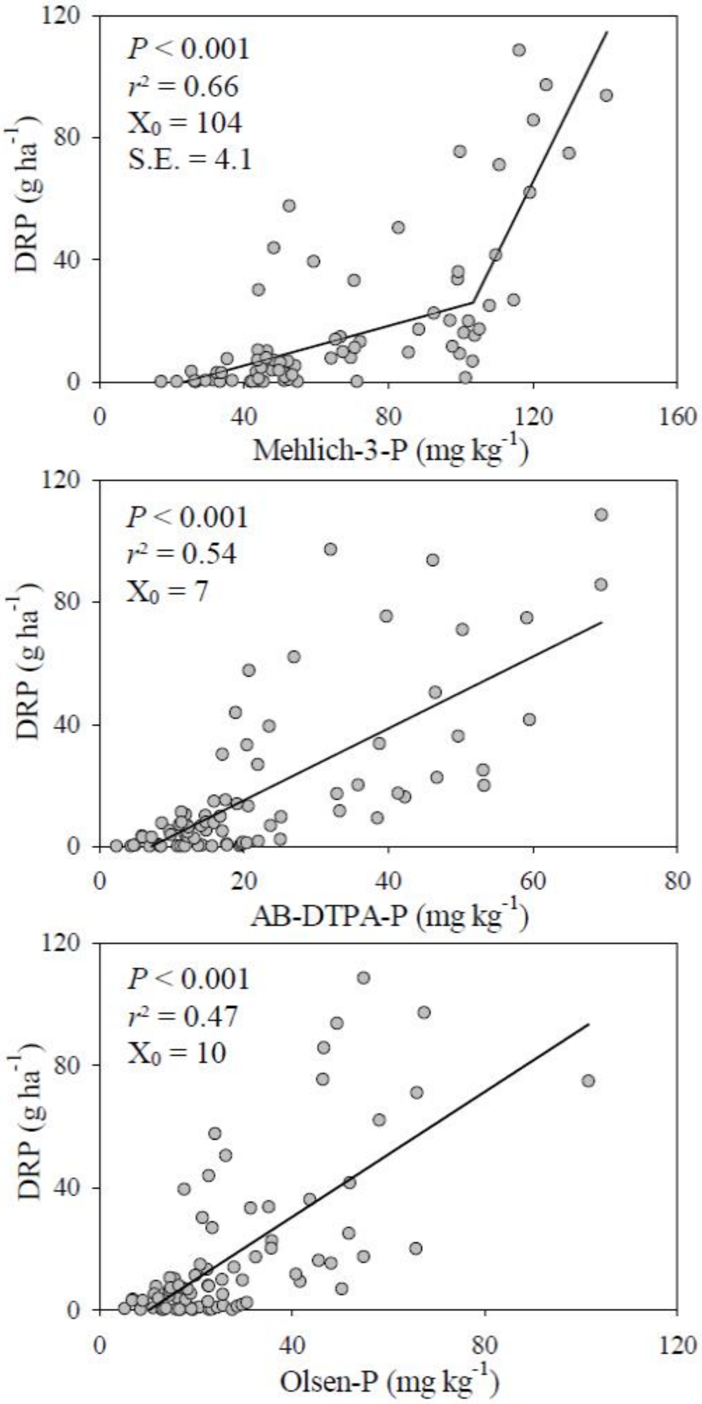

Figure 3. Relationships between soil test P extracted by Mehlich-3, AB-DTPA, and Olsen and dissolved reactive P (DRP) in leachate. Data points were the combination of the two tomato growing seasons. X_0, change point of soil test P; S.E., standard error for the change point.

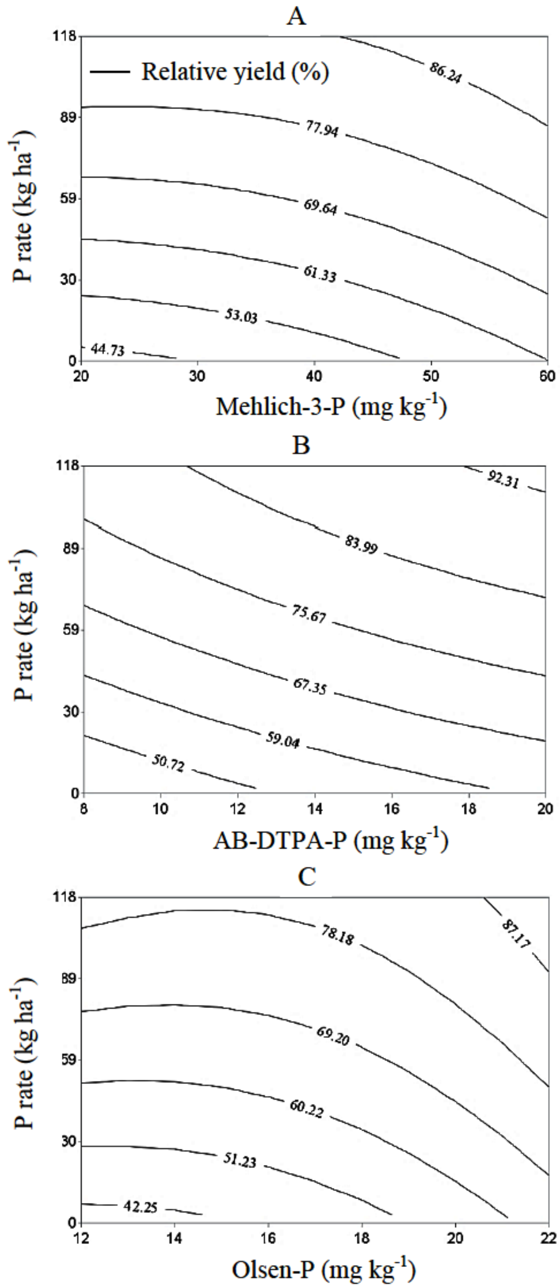

Figure 4. Tomato relative yield as estimated by multiple regression models using P fertilizer application rates and initial soil test P extracted by A) Mehlich-3, B) AB-DTPA, and C) Olsen. Data points were the combination of the two tomato growing seasons.

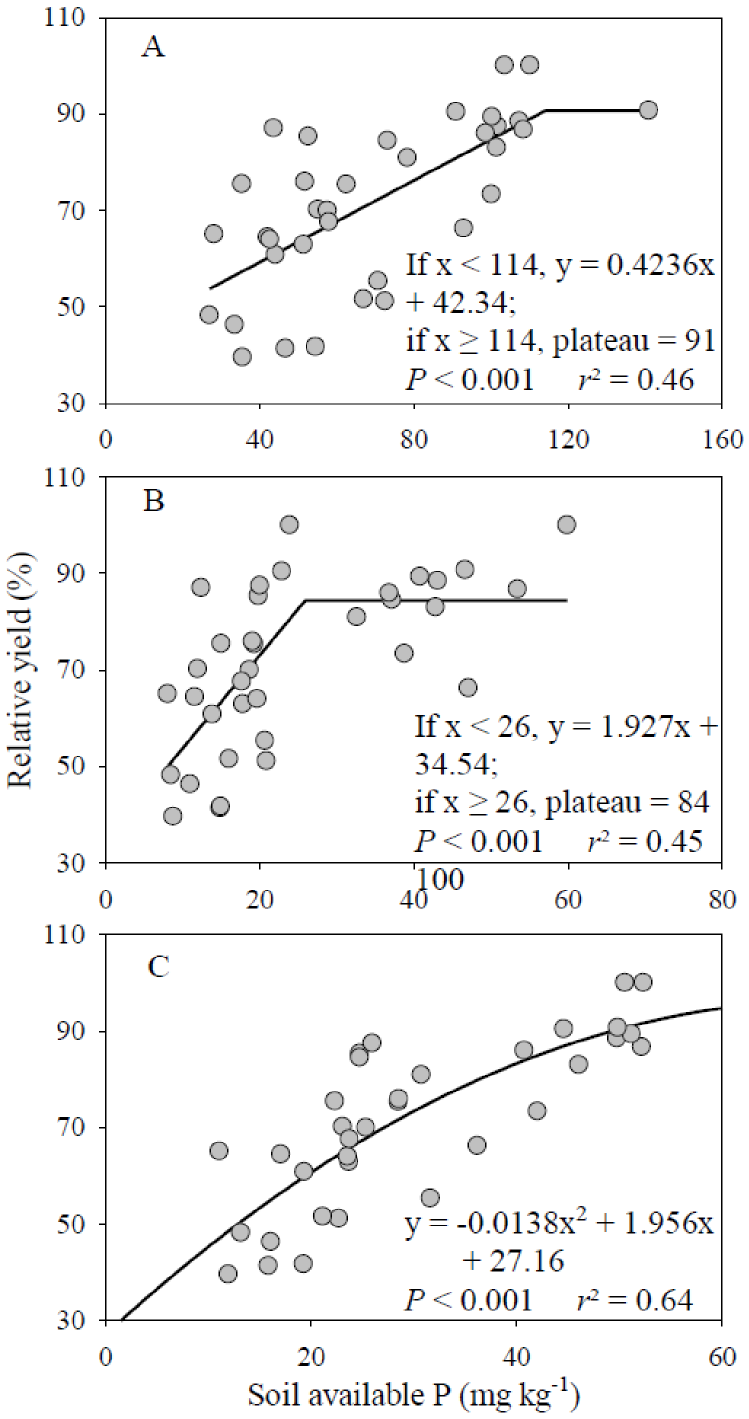

Figure 5. Relationships between tomato relative yield and soil available P (soil test P plus plant absorbed P at 30 or 40 days after pre-plant fertilization). A) linear-plateau model using Mehlich-3-P, B) linear-plateau model using AB-DTPA-P, and C) quadratic model using Olsen-P. Data points were the combination of the two tomato growing seasons.

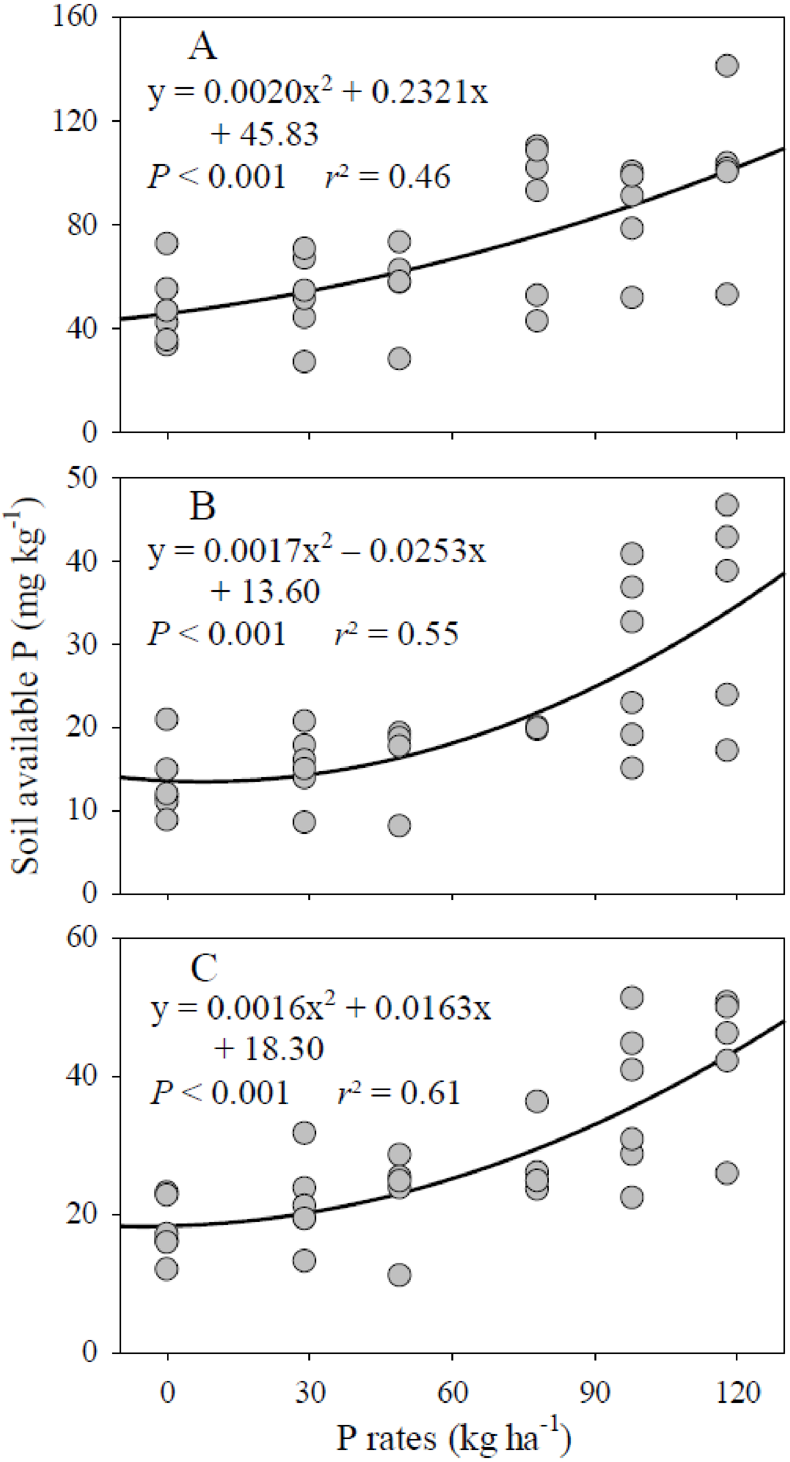

Figure 6. Quadratic response of soil available P at 30 or 40 days after pre-plant fertilization to P rates using A) Mehlich-3-P, B) AB-DTPA-P, and C) Olsen-P. Data points were the combination of the two tomato growing seasons.

Table 1. Phosphorus fertilizer application rates and soil sampling dates affected soil test P concentrations extracted by Mehlich-3, AB-DTPA, and Olsen in the year one.

DAPF†	P rate, kg P ha^{-1}						*P* value
	0	29	49	78	98	118	
mg P kg^{-1}							
Mehlich-3-P							
0	32.8	46.7 bc‡	30.5	32.8	39.5 b	37.7 b	0.42
40	43.5	40.8 c	49.3	65.5	59.3 b	66.6 b	0.39
70	46.2	36.0 c	50.0	49.8	51.2 b	41.0 b	0.64
105	36.4 D	78.6 aBC	93.0 AB	48.5 CD	98.2 aAB	119.4 aA	0.001
145	48.6 C	65.9 abABC	91.3 AB	60.2 BC	93.2 aAB	102.7 aA	0.05
P value	0.84	0.01	0.06	0.44	0.004	0.001	
AB-DTPA-P							
0	13.0	19.0 a	12.1	13.0 b	15.7	15.5	0.32
40	11.4	13.3 ab	15.2	19.7 ab	18.9	17.7	0.08
70	8.9 B	7.5 cB	12.9 B	22.6 aA	12.2 B	10.0 B	0.01
105	6.9 C	16.8 abB	19.4 B	18.9 abB	16.6 B	27.0 A	0.003
145	15.6	12.1 bc	15.7	25.9 a	22.1	20.3	0.22
P value	0.44	0.01	0.80	0.03	0.22	0.05	
Olsen-P							
0	20.0	20.9	20.4	20.0 b	20.0 c	21.4 b	0.69
40	18.6	18.7	21.5	24.6 b	31.7 bc	31.4 ab	0.26
70	17.7 B	16.7 B	21.9 AB	29.7 abA	17.3 cB	12.3 bB	0.03
105	8.2 C	32.2 ABC	40.7 ABC	22.8 bBC	64.8 aA	49.8 aAB	0.04
145	35.9	36.5	43.2	37.4 a	56.3 ab	47.2 a	0.57
P value	0.23	0.06	0.17	0.04	0.01	0.02	

† DAPF, days after preplant fertilization.

‡ Means within each column followed by different lowercase letters or within each row followed by different uppercase letters are significantly different at the 5% level.

Table 2. Phosphorus fertilizer application rates and soil sampling dates affected soil test P concentrations extracted by Mehlich-3, AB-DTPA, and Olsen in the year two.

DAPF†	P rate, kg P ha^{-1}						*P* value
	0	29	49	78	98	118	
mg P kg^{-1}							
Mehlich-3-P							
0	42.7	43.6	56.4	53.2 b‡	52.3 c	60.1 b	0.34
30	51.5 D	64.0 CD	79.2 BCD	103.6 aAB	92.1 abcABC	113.9 aA	0.01
60	55.0	76.6	75.9	95.1 a	101.3 ab	105.9 a	0.08
90	49.6 B	71.4 AB	89.2 AB	86.3 aAB	115.3 aA	115.5 aA	0.03
120	46.7	39.9	78.5	56.9 b	62.8 bc	66.5 b	0.59
P value	0.88	0.12	0.78	0.01	0.03	0.004	
AB-DTPA-P							
0	10.8	10.8	13.8	13.3 b	13.1 c	15.3 b	0.23
30	14.7 C	17.1 C	32.3 B	53.2 aA	36.3 bB	42.4 aAB	0.001
60	13.2 C	26.9 ABC	24.9 BC	34.6 abABC	44.1 bAB	50.9 aA	0.04
90	10.0 C	28.0 BC	40.3 AB	46.6 aAB	58.4 aA	50.3 aAB	0.02
120	11.1	9.6	18.1	15.4 b	12.8 c	18.9 b	0.18
P value	0.44	0.18	0.20	0.01	0.001	0.004	
Olsen-P							
0	15.0	15.8	18.3	20.4	20.2	21.3 c	0.17
30	16.7 D	23.9 CD	32.4 BC	46.6 A	40.5 AB	45.6 bAB	0.002
60	17.3 C	27.7 BC	30.2 ABC	37.2 AB	46.7 A	43.8 bcAB	0.02
90	14.7	36.8	43.9	33.0	62.4	74.3 a	0.09
120	15.0	13.2	32.8	20.2	26.3	26.2 bc	0.43
P value	0.94	0.25	0.51	0.06	0.19	0.004	

† DAPF, days after preplant fertilization.

‡ Means within each column followed by different lowercase letters or within each row followed by different uppercase letters are significantly different at the 5% level.

Table 3. Tomato marketable yield in the first harvest (FH), first and second combined harvest (FSH), and total season harvest (TSH) as affected by P fertilizer application rates.

Year	Harvest time	P rate, kg P ha^{-1}						*P* value
		0	29	49	78	98	118	
		t ha^{-1}						
One	FH	38.3 C†	36.4 C	44.6 BC	50.1 AB	51.2 AB	60.0 A	0.003
	FSH	64.1	66.5	63.4	69.2	74.7	87.2	0.09
	TSH	74.3	76.9	70.8	76.3	82.6	97.1	0.13
Two	FH	3.9 B	5.8 B	17.9 A	16.0 A	18.6 A	17.7 A	0.001
	FSH	13.4 B	15.1 B	24.4 A	25.7 A	26.0 A	25.1 A	0.001
	TSH	31.2 B	32.2 B	33.6 B	39.8 A	34.7 B	34.3 B	0.03

† Means within each row followed by different letters are significantly different at the 5% level.

Table 4. Regression coefficient of multiple regression models using tomato relative yield (%) regressed against initial soil test phosphorus (STP, mg P kg^{-1}) and P fertilizer application rate (PR, kg P ha^{-1}).

Extractant	Regression coefficient						*P* value	R^2†
	Intercept	Linear STP	Linear PR	Quadratic STP	Quadratic PR	Linear STP × PR		
Mehlich-3	41.894	-0.125	0.516	0.00743	-0.00088	-0.002455	0.001	0.70
AB-DTPA	22.724	2.711	0.476	-0.04294	-0.00111	-0.002792	0.001	0.72
Olsen	72.788	-5.658	0.6028	0.2382	-0.00088	-0.012	0.001	0.78

† R^2, coefficient of determination.

Table 5. Calculation of P index in Miami-Dade County, FL based on Hurt et al., 2013.

Part A		Part B	
Site and transport characteristics	Rating value	P source management	Rating Value
Soil erosion	1	Soil fertility index	Mehlich-3-P (mg P kg^{-1}) × 2 × 0.025
Runoff potential	2	P application rate	kg P ha^{-1} × 0.103
Leaching potential	8	Application method	0
Potential to reach water body	0	Waste water application	0
Total	11	Total	-
P index = total for part A × total for part B			

Experiment 2: Comparing Extractants for Calibrating Potassium Rates for Tomato Grown on a Calcareous Soil

Soil testing is used to assess potential availability of soil nutrients to crops. In soil testing, a universal extractant is the ideal option for extracting both macronutrients and micronutrients with a single extraction solution (Jones, 1990). Soil test interpretation usually includes three categories: low, medium, and high, at which 50 to 75%, 75 to 100%, and at or near 100% of crop yield potential can be expected, respectively, without addition of nutrients (Savoy, 2013). Using this type of rating scale, there are dramatic changes in rates of fertilizer recommendations if the soil test values are near the boundaries of adjacent ratings. Such boundary effect might be circumvented by the continuous function curves to calculate the required fertilizer with soil test results (Savoy, 2013). Potassium fertilizer recommendations based on preplant soil test are critical in ensuring crop yield and quality and minimizing fertilizer costs (Ozores-Hampton et al., 2012b). Soil K is typically divided into four forms with increasing plant availability: mineral, nonexchangeable, exchangeable, and soluble K (Havlin et al., 2014). Plants absorb K mostly from the soil solution, which is buffered by exchangeable K and ultimately by nonexchangeable forms (Wang et al., 2010).

Adopting a soil test method to estimate K fertilizer requirements is an important component of nutrient management for vegetables. Currently, there are two universal extractants used to estimate soil K availability in Florida: Mehlich-3 for acid-mineral soils and AB-DTPA for calcareous soils (Mylavarapu et al., 2014a; 2014b). Mehlich-3 was proposed as a universal extractant on a wide range of soils in the 1980s (Mehlich, 1984). In Mehlich-3 extraction solution, ammonium (NH_4^+) and hydrogen (H^+) serve to displace K^+ sorbed to the cation exchange complex. Ammonium bicarbonate-DTPA extractant was introduced for alkaline pH soils in 1977 (Soltanpour and Schwab, 1977), and similarly to Mehlich-3, NH_4^+ in AB-DTPA replaces the exchangeable K^+.

Florida ranked first in fresh market tomato production with 13,030 ha harvested and a total value of US$453 million in the year two (USDA, 2016). Current K recommendations for tomato grown on acid-mineral soils in Florida are 139, 93, and 0 kg K ha^{-1} for Mehlich-3-K rated low ($\leq$ 35 mg K kg^{-1}), medium (36-60 mg K kg^{-1}), and high ($>$ 60 mg K kg^{-1}), respectively (Freeman et al., 2014b). However, limited information regarding K recommendation is available for tomatoes grown on calcareous soils in Florida. A typical cultivated calcareous soil in south Florida is classified as Krome series (Loamy-skeletal, carbonatic, hypothermic Lithic Udorthents) by the National Cooperative Soil Survey and covers approximately 24,000 ha of agricultural land (USDA, 1996). The Krome soil usually has a 15 to 20 cm surface layer above porous limestone-bedrock and a very gravelly texture (34-76% limestone fragments, 2 mm or larger in diameter). Basic properties of this soil include high pH (7.4-8.4), high calcium carbonate content (300-940 g kg^{-1}), low organic matter content ($<$ 20 g kg^{-1}), and approximately 15% clay content (in which there are 46% hydroxyinterlayered vermiculite, 18% kaolinite, 9% quartz, and 27% calcite) (Li, 2015; Sodek et al., 1990). Carranza et al. (1996) found no response of tomato total season marketable yield (TSMY) to K fertilization on one of these calcareous soils with medium to high AB-DTPA-K. Nevertheless, the numerical soil test interpretation with AB-DTPA was not provided in that study. Water was used to extract soluble nutrients in these soils between 1960s and 1990s and the sufficient water-K concentrations for tomato production were suggested as 150-175 mg K kg^{-1} (Y.C. Li, personal communication, 2015). Hochmuth et al. (1995) used AB-DTPA, Mehlich-3, and water to predict sweet corn (*Zea mays* L.) responses to K fertilization. Their findings indicated that water was not a practical extractant due to the high variability and no yield responses were observed to K fertilization when Mehlich-3-K and AB-DTPA-K were above 42 and 91 mg K kg^{-1}, respectively.

Since no soil test procedure has been interpreted based on an effective soil test extractant, K recommendations are not available for crops, including tomato, grown on calcareous soils in Florida. Therefore, the objectives of this study were to: (i) compare the effectiveness of three extactants, Mehlich-3, AB-DTPA, and water, in testing K availability with various K rates applied in a calcareous soil; (ii) determine the relationships between STK and tomato relative yield and TKU; and (iii) calibrate K rates required to maximize tomato TSMY.

A two-year field trial was conducted as described in experiment 1. There were six K fertilizer application rates: 0, 56, 93, 149, 186, and 223 kg K ha^{-1}. Nitrogen and P were applied at the same rates for all treatments with 224 kg N ha^{-1} and 78 kg P ha^{-1}, respectively. Preplant dry fertilizers, including all the P, 25% of the N (56 kg K ha^{-1}), and portions of the K fertilizers, were banded 8 cm below and 15 cm to each side of the bed center. The remaining N (168 kg K ha^{-1}) and K (0, 56, 56, 93, 93, and 93 kg K ha^{-1} from each rate, respectively) were supplied weekly via drip fertigation from the first flowering to the first harvest (Table 1).

Soil samples were collected at the growth stages of first flowering, early fruit set, first harvest, and final harvest, which were at 40, 70, 105, and 145 DAPF in the year one and 30, 60, 90, and 120 DAPF in the year two. The initial soil sampling date (on 29 Oct. the year one and 15 Oct. the year two) before application of preplant fertilizers was considered 0 DAPF. Each soil sample was a composite of three subsamples, which were collected at 2-m intervals from one selected bed in each plot. At each sampling core, soils were taken with an auger (3 cm in diameter) from a depth of 0 to 20 cm, 10 cm away from the base of the nearest tomato plant. Soil samples were air dried, ground, and sieved through a 2 mm sieve. Soil particle size distribution was analyzed by hydrometer method. Soil pH and EC were measured at a 1:2 (w:v) ratio of soil and water using Dual Channel pH/Conductivity Meter. Carbonate and organic matter content were determined by volumetric calcimeter method (Chaney et al., 1982) and Walkley-Black method (Nelson and Sommers, 1982), respectively. Nitrate- and NH_4-N were extracted with 2 mol L^{-1} KCl (1:10 soil/extracting solution ratio) and measured using AQ2+ Automated Discrete Analyzer. Total K was measured after ignition at 550 °C and acid dissolution. Ammonium bicarbonate-DTPA extractable P was measured by the ascorbic acid-Mo blue method using spectrophotometer (Murphy and Riley, 1962). Soil test K was extracted by Mehlich-3, AB-DTPA, and water following the extraction procedures described in Table 2. Not only the chemical reagents, but also soil/solution ratio, shaker speed, and shaking time were different for the three extractants. The concentrations of K, Fe, Zn, and Mn were analyzed by an atomic absorption spectrophotometer (AA-6300; Shimadzu Scientific Instruments, Columbia, MD). At 103 DAPF in the year one and two, one entire plant sample that was visually representative of each plot was collected, and the leaf, stem, root, and fruit portions were separated to measure K uptake. All plant samples were oven-dried at 70 °C to constant weights, ground to pass a 0.84-mm sieve, digested by hydrochloric acid (Mylavarapu et al., 2014a), and analyzed for K using inductively coupled plasma-optical emission spectroscopy (Optima 7000 DV ICP-OES; PerkinElmer Inc., Waltham, MA). Total K uptake was the sum of uptakes in each plant tissue, which was calculated from multiplying K concentration by the related dry weight. Tomato fruits from ten plants in the middle bed of each plot were harvested three times at the mature-green stage at 119, 133, and 146 DAPF in the year one and 96, 110, and 124 DAPF in the year two. Unmarketable fruits (culls) were excluded based on the symptoms described by Olson and Freeman (2016). Total season marketable yield was the weight of marketable fruits categorized as extra-large (diameter larger than 7 cm), large (diameter from 6.4 to 7.1 cm), and medium (diameter from 5.7 to 6.4 cm) from the three harvests (USDA, 1997). Relative yield was calculated by dividing each season’s actual TSMY by its maximum TSMY among all the plots, which were 100 and 43 t ha^{-1} in the year one and two, respectively.

Studentized Deleted Residuals (< -3 and > 3) were used to identify potential outliers in STK values. Five extremely high STK concentrations were identified as outliers probably because of residual fertilizer in the soil samples. These outliers were omitted before statistical analysis.

Analysis of variance in the effects of K rates or sampling dates on STK, TKU, and TSMY were performed using SAS (Version 9.2; SAS Institute Inc., NC). When *F* tests showed statistical significance ($P < 0.05$), the means among various K rates or sampling dates were separated by the Duncan’s Multiple Range Test. A simple linear regression model was used to evaluate the correlation of STK by the three extractants. Two approaches were performed to calibrate required K rates with tomato relative yield. For the first approach, a multiple regression model that included the linear and quadratic terms for initial STK (at 0 DAPF) and K rate plus the linear interaction term (initial STK × K rate) (Relative yield = a + b×STK + c×K rate + d×STK^2 + e×K $rate^2$ + STK×K rate) was used to predict tomato relative yield against the combination of initial STK and K rate (Slaton et al., 2009). The second approach used four regression models (linear, quadratic, linear-plateau, and quadratic-plateau) to analyze the relationships between tomato relative yield and total K input. Total K input in each plot was calculated by adding full-season K rate to initial STK concentration, in which the unit mg K kg^{-1} was transformed to kg K ha^{-1} using a soil bulk density of 1.2 g cm^{-3} and a depth of 20-cm. The model with $P < 0.05$, lower mean square error, and higher coefficient of determination (r^2) was selected as the best fit regression model (Ozores-Hampton et al., 2012a). Relationships between total K input and TKU were analyzed by the above four models as well. The very low STK level was defined as the concentrations producing less than 50% tomato relative yield. The relative yield of 75% was used to distinguish between low (producing 50 to 75% relative yield) and medium (producing 75 to 95% relative yield) soil test rating categories (Savoy, 2013). According to Slaton et al. (2010), the relative yield of 95% was set as the optimum yield goal to calculate required K rates.

Mehlich-3-K concentrations were significantly affected by K rates at 70 and 105 DAPF in the year one and at 30, 60, and 90 DAPF in the year two (Table 3 and 4), whereas there were no significant responses of Mehlich-3-K to K rates at the end of both years. At 40 and 145 DAPF in the year one, neither AB-DTPA-K nor water-K concentrations were significantly affected by K rates. During all sampling dates in the year two, concentrations of AB-DTPA-K with K rate of 223 kg K ha^{-1} were significantly higher than those with the rates of 0 and 56 kg K ha^{-1}. The responses of water-K to K rates were not significant from 30 to 120 DAPF in the year two. Initial STK concentrations (at 0 DAPF), averaged from all K rates in the year two, decreased by 12, 4, and 54% for Mehlich-3-K, AB-DTPA-K, and water-K, respectively, compared with the initial concentrations in the year one. In the absence of K fertilizer, the means of Mehlich-3-K and AB-DTPA-K at the end of both years significantly decreased by 43 to 52% and 30 to 45% compared with initial concentrations, respectively. However, the differences of water-K between 145 and 0 DAPF were not significant in both years at K rate of 0 kg K ha^{-1}. With K rate of 223 kg K ha^{-1}, no significant differences were found for both Mehlich-3-K and AB-DTPA-K during all the sampling dates of the year one and the year two, but water-K at 40, 70, and 105 DAPF were significantly higher than at 145 DAPF in the year one. Combining two years' data together, the amounts of soil K extracted by the three extractants were significantly correlated (Fig. 1). The highest correlation occurred between Mehlich-3-K and AB-DTPA-K ($r^2 = 0.78$) and the lowest correlation was observed between AB-DTPA-K and water-K ($r^2 = 0.39$). Due to the low correlations between water-K and Mehlich-3 and AB-DTPA extracted K, the calibration approaches were performed only for Mehlich-3-K and AB-DTPA-K.

Total K uptake (at 103 DAPF) and tomato TSMY were significantly higher with K rates at and above 149 kg K ha^{-1} than those with K rates below 149 kg K ha^{-1} in both years (Table 5). In the multiple regression calibration approach, the two models were significant and explained 77 and 75% of tomato relative yield variability as affected by the combination of K rate and initial STK extracted by Mehlich-3 and AB-DTPA, respectively (Table 6; Fig. 2). These models predicted that 50% tomato relative yield would be obtained at K rate of 0 kg K ha^{-1} and 83 and 72 mg K kg^{-1} of Mehlich-3-K and AB-DTPA-K, respectively. When 75 and 95% relative yield were produced without K fertilization, AB-DTPA-K were predicted to be 103 and 117 mg K kg^{-1}, respectively. The model using Mehlich-3-K could not predict the required STK concentration to produce 75% or higher relative yield without K fertilization. Potassium rates of 277 and 136 kg K ha^{-1} were predicted to achieve 95% relative yield for soils having 72 and 103 mg K kg^{-1} of AB-DTPA-K, respectively.

Relationships between total K input (initial STK plus full-season K rate) and TKU were described by linear models using both Mehlich-3-K and AB-DTPA-K (Fig. 3). Total K input explained 87 and 81% of TKU variability indicated by the linear models using Mehlich-3-K and

AB-DTPA-K, respectively. The responses of tomato relative yield to total K input were predicted by quadratic models using Mehlich-3-K and AB-DTPA-K (Fig. 4). According to the quadratic models, total K input calculated by Mehlich-3-K and AB-DTPA-K accounted for 75 and 74% of the variation in tomato relative yield, respectively. Calculated from the quadratic equations, total K input of 511 kg K ha^{-1} (equivalent to 213 mg K kg^{-1}) and 439 kg K ha^{-1} (equivalent to 183 mg K kg^{-1}) were needed to produce 95% relative yield using Mehlich-3-K and AB-DTPA-K, respectively. Total K input of 361 kg K ha^{-1} (150 mg K kg^{-1}) and 287 kg K ha^{-1} (120 mg K kg^{-1}) were predicted to produce 75% relative yield, as calculated by Mehlich-3-K and AB-DTPA-K, respectively. Fifty percent of relative yield was produced when total K input were 203 kg K ha^{-1} (85 mg K kg^{-1}) and 167 kg K ha^{-1} (70 mg K kg^{-1}) calculated by Mehlich-3-K and AB-DTPA-K, respectively.

The calcareous soils in this study, with 1423 mg K kg^{-1} of total K and a 46% vermiculite clay fraction, had high K buffering capacity. High soil K buffering capacity results in high K fixation as well as high K releasing capacity (Wang et al., 2010). As a result, the non-exchangeable K fraction can be potentially released. In addition, exchangeable K can be displaced by the cations present in the extractant. Thus, extracted K from this type of calcareous soil probably included all of the soluble K, most of the exchangeable K, and small proportions of the nonexchangeable K. Without K fertilization, Mehlich-3-K and AB-DTPA-K concentrations at the end of each season were significantly lower than at the beginning, which was attributed to tomato plant uptake and potential leaching; nonetheless, there were no significant differences in water-K. The average initial STK concentrations in the year two were only 12 and 4% lower than that in the year one for Mehlich-3-K and AB-DTPA-K, respectively, but the initial water-K decreased by 54% compared with that in the year one. Furthermore, differently from Mehlich-3-K and AB-DTPA-K, water-K was not significantly affected by K rates from 30 to 120 DAPF in the year two. These results indicated that similarly to Mehlich-3 and AB-DTPA, water possibly extracted exchangeable and nonexchangeable K forms as well.

Based on the significant linear correlations among STK concentrations extracted by the three extractants, Mehlich-3 extracted more K than AB-DTPA, and a similar amount of K as water. A similar correlation between Mehlich-3 and AB-DTPA in determining STK was found by Liu and Bates (1990) and Bibiso et al. (2015). The higher amount of K extracted by Mehlich-3 than AB-DTPA was mainly attributed to the combination of acidity and ammonium salts in Mehlich-3 extraction solution as stated by Elrashidi et al. (2003). On the other hand, Woods et al. (2005) concluded that water (1:5 soil to solution ratio with 30-minute shaking time) extracted less K than Mehlich-3 in calcareous sands, and Hosseinpur and Zarenia (2012) showed a lower amount of K extracted by water (1:10 soil to solution ratio with 30-minute shaking time) than AB-DTPA in calcareous soils. According to Woods et al. (2005), more K was extracted by an extraction method with a lower soil to solution ratio and longer shaking time because extra K was exchanged with further dissolved Ca and Mg in calcareous soil. In this experiment, K was extracted by water using a 1:10 soil to solution ratio and a 60-min shaking time; hence, water, as compared to AB-DTPA, was predicted to extract higher amounts of K. Furthermore, the low correlations between water-K and Mehlich-3 and AB-DTPA extracted K indicated the high variability of water-K. Consequently, water was considered an ineffective extractant to estimate

K availability in the studied calcareous soils, which was consistent with the conclusion from Hochmuth et al. (1995). However, Hosseinpur and Zarenia (2012) found water-K correlated better with pinto bean (*Phaseolus vulgaris* L.) relative yield than AB-DTPA-K in calcareous soils. These discrepancies might be attributed to the different water extraction procedures and various calcium carbonate contents in different calcareous soils.

Tomato TKU and relative yield were used to regress against STK concentrations extracted by Mehlich-3 and AB-DTPA. Slaton et al. (2009, 2010) showed a contour graph made from a multiple regression model could provide reasonably accurate K recommendation rates based on relative yields and initial STK concentrations. The multiple regression models were significant for the combination of K rate and STK by the two extractants in the present experiment. Through this approach, the very low initial STK levels (producing less than 50% tomato relative yield) were identified as being below 83 and 72 mg K kg^{-1} for Mehlich-3-K and AB-DTPA-K, respectively. The other approach adopted total K input (initial STK plus full-season K rate), in which the values of STK and K rate could be transferred to each other (multiplying by 2.4 for transferring mg K kg^{-1} to kg K ha^{-1}), to predict critical STK concentration and K rates. Significantly linear correlations were found between TKU and total K inputs using both Mehlich-3-K and AB-DTPA-K. Similar r^2 were detected in the linear relationships using Mehlich-3-K and AB-DTPA-K. These results were in agreement with the findings of Liu and Bates (1990), which used Mehlich-3-K and AB-DTPA-K to predict TKU in alfalfa (*Medicago sativa* L.). Quadratic models predicted significant relationships between total K input and relative yield. Calculated from the quadratic model, the low scale of initial AB-DTPA-K was from 70 to 120 mg K kg^{-1}, which covered the scale from the multiple regression model (from 72 to 103 mg K kg^{-1}). The medium rating scale of AB-DTPA-K was predicted from 120 to 183 mg K kg^{-1}, which was higher than the medium category (from 61 to 120 mg K kg^{-1}) in AB-DTPA soil test interpretations from Colorado (Soltanpour, 1985). The adequate soil K concentration of 183 mg K kg^{-1}, at which K fertilization was not required, was also higher than that value (91 mg K kg^{-1}) for sweet corn found by Hochmuth et al. (1995). These variations might be due to the differences in soil K buffering capacity and K requirement by crop. The low and medium rating scales for Mehlich-3-K were predicted from 85 to 150 mg K kg^{-1} and from 150 to 213 mg K kg^{-1}, respectively, which were also higher than the corresponding values in acid-mineral soils in Florida. The predicted STK concentrations to produce 50% relative yield were similar between the two calibration approaches using both Mehlich-3-K and AB-DTPA-K.

Hosseinpur and Samavati (2008) showed that AB-DTPA-K in soils with pH ranging from 7.0 to 8.1 was not significantly correlated with field corn (*Zea mays* L.) relative yield and plant K concentration in a greenhouse pot study. In the present field study, however, total K inputs using both Mehlich-3-K and AB-DTPA-K were significantly correlated with tomato relative yield and TKU. Therefore, both Mehlich-3 and AB-DTPA could be acceptable as soil K extractants for calcareous soils in Florida. Calculated from the required total K input of 439 kg K ha^{-1} (or 183 mg K kg^{-1}) using AB-DTPA-K to produce 95% tomato relative yield, the required K rates were 271 and 151 kg K ha^{-1} when AB-DTPA-K were 70 and 120 mg K kg^{-1}, respectively. The K rates predicted by the quadratic model were similar to those (136-277 kg K ha^{-1}) predicted by the multiple regression model at low level of AB-DTPA-K. For the low level of Mehlich-3-K, required K rates were predicted from 151 to 307 kg K ha^{-1}, which was higher than that (139 kg K ha^{-1}) for acid-mineral soils in Florida. Optimum tomato yield in calcareous soils required higher K rates probably due to the K fixation by clay minerals and the antagonism among K, Ca, and Mg in nutrient uptake (Mengel and Kirkby, 1987; Jifon and Lester, 2009).

Conclusions

Relationships of STK extracted by Mehlich-3, AB-DTPA, and water were evaluated among them and with TKU and relative yield of tomato grown on a calcareous soil in Florida. The highest correlation occurred between Mehlich-3-K and AB-DTPA-K. Relationships between TKU and total K input (initial STK plus full-season K rate) were predicted by linear models for both Mehlich-3-K and AB-DTPA-K. The quadratic models predicted that tomato relative yield would reach 95% when initial Mehlich-3-K and AB-DTPA-K were 213 (equivalent to 511 kg K ha^{-1}) and 183 mg K kg^{-1} (equivalent to 439 kg K ha^{-1} of K), respectively. Therefore, total K input of 511 and 439 kg K ha^{-1} can be considered the standards to calculate required K rates based on initial STK concentrations using Mehlich-3-K and AB-DTPA-K, respectively. At the low soil test rating scale, recommended K rates were from 307 to 151 kg K ha^{-1} with 85 to 150 mg K kg^{-1} of Mehlich-3-K and from 271 to 151 kg K ha^{-1} with 70 to 120 mg K kg^{-1} of AB-DTPA-K, respectively.

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Experiment 3 Snap Bean Field Trial

Agricultural Best Management Practices (BMPs) are designed to improve water quality by reducing the amount of nutrients and other pollutants while maintaining agricultural production. The vegetable BMPs have adopted all current University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) recommendations, including those for fertilizer and irrigation management. Utilizing soil testing to determine crop nutrient requirements is an important part of vegetable crops BMPs. The objective of the soil testing is to provide fertilizer recommendation that is sound considering both economic and environmental impacts. Until now, due to the lack of research data and non- official extractant for calcareous soils, no nitrogen (N), phosphorus (P), potassium (K) and other nutrients recommendations can be provided for vegetable production in Miami-Dade County. UF/IFAS Extension Soil Testing Laboratory (ESTL) received more and more samples which classified as calcareous soils (high pH and high calcium carbonate content) throughout Florida.

A field with low concentrations of soil P and K was selected based on analyses of soil samples collected throughout the research farm at UF/IFAS/Tropical Research and Education Center (TREC). The fertilizer application rates were 0, 50, 75, 100, 150, and 200 lb N/acre; 0, 60, 80, 120, 160, and 200 lb P_2O_5/acre; and 0, 60, 80, 120, 160, and 200 lb K_2O/acre. Nitrogen, P, and K were supplied at 100, 120, and 120 lb/acre, respectively, if they were not treatment factors. Treatments were arranged in a randomized complete block design with four replications. All cultural practices except fertilizer application were managed according to the UF/IFAS recommendations for tomato production, including irrigation and pest management (Table 1). Dry-weight biomasses were collected at 44 days after seeding (DAS) and divided into aboveground and root sections. Snap beans were harvested from 30 plants in each plot at 69 DAS. Data were analyzed using SAS (version 9.3; SAS Institute Inc, Cary, NC).

Average air temperatures were 74.9 °F and total rainfall was 7.6 inches during snap bean growing season (Table 4). One leaching rainfall event (three inches in three days or four inches in seven days) was recorded.

Neither snap bean yields nor biomass accumulations were significantly affected by different N, P, and K rates, respectively.

Unfortunately, the field trial for snap bean was affected by disease problem. Neither snap bean yields nor biomass accumulations were significantly affected by fertilizer treatments.

Table 1. Summary of cultural practices used for evaluating nitrogen, phosphorus, and potassium rates on snap bean.

Location	Block 11 (North), TREC, Homestead, FL.
Experimental design	RCBD (4 replications)
Irrigation	Sprinkle
Plot size	30 ft * 6 beds = 180 ft
Harvest unit	30 plants in each plot
Total area	30 feet * 6 beds (18 feet width)* 68 plots = 0.843 acre
Pre-emergence herbicide	Spray Sandea at 1 oz/acre with 15 gal water after planting but prior to soil cracking
Variety	Momentum (SB4534)
Distance between rows	3 ft (LBF = 14,520)
Plant spacing	4 inches
Plant density	90/row/plot = 36,720 total
Seeds	36720/0.85 (germ rate) = 43200*0.2 (g per seed) = 8.64 kg

Table 2. Characteristics of soils collected from the experimental site before applying fertilizers.

Gravel (> 2mm) (%)		54.3 - 72.2
Clay (%)		8.4
Silt (%)		13.2
Sand (%)		78.4
pH (water)		7.8
Electrical conductivity (µS/cm)		248.2
Carbonate (g/kg)		379.3
Organic matter (g/kg)		56.9
Total nitrogen (mg/kg)		3163.3
Nitrate-nitrogen (mg/kg)		22.3
Ammonium-nitrogen (mg/kg)		7.2
Total phosphorus (mg/kg)		1472.7
Total potassium (mg/kg)		1422.7
AB-DTPA[z] extracted	Phosphorus (mg/kg)	14.7
	Potassium (mg/kg)	81.5
	Iron (mg/kg)	6.3
	Zinc (mg/kg)	6.7
	Manganese (mg/kg)	11.1

[z] AB-DTPA = ammonium bicarbonate-diethylenetriaminepentaacetic acid.

Table 3. Treatments of nitrogen (N), phosphorous (P) and potassium (K) used to grow snap beans during spring season in Homestead, FL.

Treatment	N (Urea)		P_2O_5 (TSP)		K_2O (K_2SO_4)	
	Rate (lb/acre)	Banding 20% at seeding/40% first trifoliate leaf/40% first flower bud	Rate (lb/acre)	Banding 100% at seeding	Rate (lb/acre)	Banding 50% at seeding/50% at first flower bud
T1	0	0	120	120	120	60/60
T2	50	10/20/20	120	120	120	60/60
T3	75	15/30/30	120	120	120	60/60
T4	100	20/40/40	120	120	120	60/60
T5	150	30/60/60	120	120	120	60/60
T6	200	40/80/80	120	120	120	60/60
T7	100	20/40/40	0	0	120	60/60
T8	100	20/40/40	60	60	120	60/60
T9	100	20/40/40	80	80	120	60/60
T10	100	20/40/40	160	160	120	60/60
T11	100	20/40/40	200	200	120	60/60
T12	100	20/40/40	120	120	0	0
T13	100	20/40/40	120	120	60	30/30
T14	100	20/40/40	120	120	80	40/40
T15	100	20/40/40	120	120	160	80/80
T16	100	20/40/40	120	120	200	100/100
T17 Control	0	0	0	0	0	0

Fertilizer sources: urea (46%); triple superphosphate (TSP, 40%); and K_2SO_4 (50%).

Table 4. Summary of average, minimum (Min) and maximum (Max) temperature and total rainfall in Homestead, FL.

Period	Temperature (°F)			Total rainfall (inches)	Number of leaching rainfall[z]
	Average	Min.	Max.		
February	72.7	64.3	84.1	0	0
March	73.3	63.4	84.5	1.9	0
April	77.2	67.4	87.5	5.7	1
May	73.2	63.0	81.7	0	0
Average/Total	74.9	65.1	85.6	7.6	1

Weather data obtained from Florida Automated Weather Network (FAWN) from University of Florida/Institute of Food and Agriculture Science (IFAS), Tropical Research and Education Center in Homestead, FL. [z]A leaching rain is defined as a rainfall amount of 3 inches in 3 days or 4 inches in 7 days.

Table 5. Responses of snap bean yield and biomass to nitrogen (N), phosphorous (P) and potassium (K) application rates.

N rate	Yield	Dry-weight biomass	
		Aboveground	Root
(lb/acre)			
Control	5027.0	1484.7	71.4
0	5566.1	1505.7	79.4
50	5466.3	1287.2	73.5
75	5993.3	1641.3	64.8
100	5402.4	1168.7	59.0
150	4631.7	1202.6	57.4
200	5274.6	924.4	45.7
P value	0.96	0.33	0.17

P_2O_5 rate	Yield	Dry-weight biomass	
		Aboveground	Root
(lb/acre)			
Control	5027.0	1484.7	71.4
0	5238.7	1011.2	56.0
60	5234.7	1037.7	59.8
80	5901.5	1343.3	60.5
120	5402.4	1168.7	59.0
160	6672.1	1413.2	80.2
200	6528.4	1447.3	73.3
P value	0.70	0.15	0.57

K_2O rate	Yield	Dry-weight biomass	
		Aboveground	Root
(lb/acre)			
Control	5027.0	1484.7	71.4
0	4775.5	1314.7	62.7
60	5118.9	1239.9	65.6
80	4919.2	1308.2	71.3
120	5402.4	1168.7	59.0
160	5893.5	1464.8	69.9
200	7139.3	1197.5	58.4
P value	0.30	0.87	0.90

Overall Conclusions

Tomato crop did not respond to soil application of additional phosphorus or potassium above the current IFAS recommendations in north Florida acid sandy soils. These studies validated the current IFAS soil test level interpretations and phosphorus and potassium recommendations for acid-mineral soils for using Mehlich-3 procedure.

The significant positive responses of tons sugar/acre to potassium fertilizer at several locations of the potassium sandland sugarcane study are a strong indication that we should be able to develop an updated soil test calibration for potassium for these soils. We are testing three different soil extractants and early results suggest that a reliable relationship can be developed between soil test potassium and sugarcane yield. In the phosphorus sandland sugarcane study, there have been fewer significant sugarcane yield responses to phosphorus fertilizer, but there have been yield responses and there has been a wide range of initial soil test phosphorus. More data are needed but with the seven locations of this trial we should be able to develop a useful relationship between soil test phosphorus and sugarcane yield. The Mehlich-3 soil extractant showed promise for the sugarcane on sandlands and the data suggests that the current rates for phosphorus and potassium are sufficient and do not need to change.

Based upon the studies for which a comparison between the extractants was made, Mehlich-3 appeared to be a suitable substitute for the water extraction currently used for phosphorus for vegetable production in muck soils. Mehlich-3 generated similar yield response curves to phosphorus through water extraction.

Mehlich-3 was an effective extractant to simultaneously estimate P and K availability in calcareous soils. Overall, 75 kg ha^{-1} of P and 178 kg ha^{-1} of K were sufficient to grow tomato during the winter season in calcareous soils with 37-51 and 99-112 mg kg^{-1} of Mehlich-3 extractable P and K, respectively. This data can form the basis to develop new interpretations for vegetable production on calcareous soils of Florida.