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Improving methods for evaluating potassium availability in vineyard soils

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Abstract

Vineyard soils often contain mineralogy that can confound predictions of plant-available potassium (K). Too little or too much K uptake into wine-grape (*Vitis* varieties) tissues can negatively affect fruit chemistry, making it important to have soil tests that accurately quantify plant-available K. Our goal was to determine the best soil sampling, processing, and extraction methods for predicting K availability in vineyard soils. We sampled soil and grapevine tissue in 39 vineyard blocks from 22 vineyards in Virginia, Maryland, and New Jersey. Plant tissue sampling included petioles at bloom and both petioles and leaf blades at veraison. Soil samples were collected from 0 to 10- and 0 to 38-cm depths. We tested three soil extraction methods—Mehlich 1, Mehlich 3, and sodium tetraphenylboron (NaTPB)—on both oven-dried and field-moist samples. The different sampling, processing, and extracting procedures produced distinct K concentrations, with shallow 0–10 cm samples and NaTPB extraction resulting in higher K concentrations than their counterparts. Upon drying, three soils fixed K and 24 samples released K. Whole leaf (petiole plus leaf blade) samples collected at veraison had the best relationships with most soil K concentrations. The best soil testing method for predicting tissue K concentration in whole leaves at veraison was Mehlich 1 extractions of field-moist soils from 0 to 38-cm depth. This sampling combination appears to be best suited for growers to use when assessing K concentrations in vineyard soils.

1 | INTRODUCTION

Soil analyses for potassium (K) are used to evaluate new vineyard sites and track long-term vineyard soil fertility and chemistry. Potassium is an essential nutrient involved in many important grapevine (*Vitis* varieties) functions including photosynthesis, plant water movement, and fruit ripening (Kant & Kafkafi, 2002; Keller, 2015), but predicting its availability is challenging. Multiple factors complicate predicting K uptake both in the soil and vine. The recommended routine soil sampling, processing, and testing methods in the Mid-Atlantic United States often underestimate K concentrations (overstating the need for K fertilizer) even as vine tissue analyses have high or very high K concentrations (Beasley et al., 2017; Boynton et al., 1958; Wolf, 2016).

Potassium deficiencies are rarely seen but excessive K is common in the Mid-Atlantic United States (Beasley et al., 2017; Wolf, 2008, 2016). This region spans the Coastal Plain, Piedmont, Blue Ridge, and Ridge and Valley, and

Abbreviations: ICP, inductively coupled plasma spectroscopy; NaTPB, sodium tetraphenylboron.

Appalachian Plateau, all of which may include soils that contain minerals that can provide K to vines (Bertsch & Thomas, 1985; Flock, 1963). Similar soils exist in the southern and midwestern United States as well as other wine regions of the world including California (O'Geen et al., 2008; Rees et al., 2013), Australia (Mpelasoka et al., 2003), and parts of Africa and Europe (Maltman, 2022).

Accurately predicting K is important to growers because K can negatively affect grape and wine chemistry. Fruit with K concentration greater than 1242 mmol/L results in less free acid and undesirably high fruit juice pH (i.e., >3.65), which can negatively affect wine taste, mouthfeel, color intensity, color hue, and shelf life (Kant & Kafkafi, 2002; Mpelasoka et al., 2003; Hepner & Bravdo, 1985; Walker & Clingeleffer, 2016). Fruit pH is correlated with both fruit and tissue K, which is affected not only by soil availability but also crop load, canopy size and sunlight exposure, variety, rootstock, weather, and other factors (Morris et al., 1980; Mpelasoka et al., 2003; Walker & Blackmore, 2012). Some strategies exist to counteract high pH, but they can affect wine taste and storage life, making it best to reduce excessive K uptake in the vineyard (Kemp, 2017; Mpelasoka et al., 2003).

Sample processing is an important factor influencing measurements of soil K concentrations. Routine soil analyses use air-dried soil samples but the drying process can affect K availability, particularly in soils containing illite and vermiculite. These minerals store K in structural cavities between interlayers that can be released or fixed into mineral structures depending on the hydration status of K ions as well as competition with other ions (Barber, 1984; Peacock, 2007; Sparks, 2003). Whether K will be released or fixed depends on the type of mineral, the weathering status of that mineral, and soil solution K concentration (Barbagelata & Mallarino, 2013; Rees et al., 2013; Simonsson et al., 2009). In general, soils that have solution K ≥100 mg/kg are likely to fix K upon drying and subsequent extraction, and analyses may underestimate field-moist soil K concentration (Haby, 1975; Wells & Dollarhide, 2000). Moist extraction, in which soil is analyzed at its field-sampled water content, is an alternative that may be better able to predict vine-available K because it avoids K release or fixation that occurs during drying (Barbagelata & Mallarino, 2013).

Different soil test extractants also influence soil analysis results. Extractants are formulated based on regional-scale soil properties and are usually geographically limited in their applicability. For example, Mehlich 1, which is a dilute solution of HCl and H_2SO_4, was developed for coarse-textured soils (Mehlich, 1953). Mehlich 3, which uses an extraction solution of CH_3COOH, NH_4F, HNO_3, EDTA, and NH_4NO_3, was formulated for use in a wider range of soil textures, and it generally extracts more soil K because of the presence of the same-charged and similarly sized NH_4 ion (Mehlich, 1984). Sodium tetraphenylboron (NaTPB) has been successfully used as an alternative to Mehlich 3 in soils dominated by 2:1 K-fixing mineralogy because it can extract a portion of nonexchangeable, possibly plant-available K (Scott et al., 1960). No known research has investigated which extractions are most effective for predicting grapevine-available K (Haby et al., 1990; Sharpley, 1989).

Core Ideas

- Extractions from field-moist soils had best correlation with grapevine tissue potassium (K) concentration.
- Soil samples collected from 0 to 38-cm depths best predicted grapevine tissue K concentration.
- Soil K extracted via Mehlich 1 had better correlation with vine tissue K concentration than Mehlich 3 or sodium tetraphenylboron.

In addition to soil analyses for determining potential nutrient availability to grapevines, vine tissue analyses are used in established vineyards to evaluate the nutritional status of grapevines and make necessary corrections. Most Eastern United States practitioners collect petioles at either full bloom or veraison (the onset of fruit ripening, typically occurring in late July or early August), depending on the nutrient of interest (Wolf, 2008). Petiole analyses were adopted by the United States and Australia, but European countries and some Western US states typically collect leaf blades (Bennett, 1993; Schreiner & Scagel, 2017). Tissue types and timings specifically for K status of vines have not been extensively compared in the Eastern United States, even though tissue analyses frequently contradict soil analysis recommendations, creating confusion among growers (Beasley et al., 2017; Wolf, 2016). The lack of correlation among soil K, tissue K, and plant response (in our case, vine uptake and fruit chemistry) has been observed in other crops and regions (Barbagelata & Mallarino, 2013; Rees et al., 2013; Simonsson et al., 2009).

The overall goal of this project was to evaluate and improve recommended soil sampling, handling, and testing methods. This goal required us to evaluate correlations between vine tissue K and soil K. Our specific objectives were to (1) survey established vineyard soils for their K concentrations according to different soil sampling/processing/extracting methods, (2) determine the general behavior of Mid-Atlantic soils upon drying, (3) evaluate the effects of sampling depth and drying on plant-available K for use in soil sampling/processing protocols, and (4) identify the soil extraction method that best predicts K concentration in grapevine tissues. Previous work has theorized that the lack of correlations between soil K and tissue K noted in the Mid-Atlantic (Beasley et al., 2017; Wolf, 2016) reflects the ability of vines to access nonexchangeable K in the subsoil. Therefore, we hypothesized that soil K from Mehlich 3 and NaTPB extractions would better predict tissue

K because those extractions were likely to produce higher K concentrations than the Mehlich 1 extraction.

2 | METHODS

2.1 | Sample locations

Twenty two commercial and research vineyards throughout Virginia, Maryland, and New Jersey were recruited to participate in this research (Table 1), including a range of soils to obtain a wide distribution of soil K concentrations. We sampled multiple vineyard blocks (single varieties) within some of those vineyards. The final set of experimental units included 39 vineyard blocks representing four physiographic provinces: Coastal Plain (three blocks), Piedmont (19 blocks), Blue Ridge (five blocks), and Ridge & Valley (12 blocks).

2.2 | Wine grape varieties

We worked exclusively with red-fruited varieties. These were primarily *Vitis vinifera* varieties (12 Cabernet Franc, 11 Merlot, 8 Petit Verdot, 2 Cabernet Sauvignon, and 1 each of Malbec, Tannat, Teraldago, and Sangiovese), with several French American hybrids (4 Chambourcin, 1 Maréchal Foch, and 1 Landot Noir; see Table 1). Five of the samples were from a replicated variety trial. Unless noted in Table 1, vineyards were vertical shoot position trained with herbicide strips beneath vine rows. We attempted to collect yield and pruning weights data, but the number of sites and slight differences in vineyard management made it difficult. Yield data were confounded by crop thinning practices (i.e., removing fruit mid-growing season to prevent overcropping). All vineyards employed some form of crop thinning, but the timing was not consistent. Pruning weight data were confounded by hedging practices since all vineyards hedged to some degree.

2.3 | Vine sample collection and processing

All samples were collected in 2020. For 18 of the blocks, we collected at least 50 random full bloom petiole samples from leaves directly opposite the primary cluster. At veraison (i.e., when approximately 50% of berries had started to change color), we randomly collected a minimum of 50 petiole and leaf blades from fully expanded leaves (5–7 leaves down from the shoot tip). We separated petioles and leaf blades, rinsed them first with soapy water and then distilled water, and then oven-dried the samples at 40°C for at least 24 h. We weighed the samples, then they were ground, digested with concentrated nitric acid, and analyzed for K in duplicate via inductively coupled plasma spectroscopy (ICP) according to the methods of Huang and Schulte (1985).

We calculated whole-leaf K concentration as a weighted average. First, we calculated the proportions of leaf blade and petiole mass in each tissue sample as follows:

$$\text{Leaf blade proportion} = \frac{\text{Mass leaf blades(g)}}{\text{Total mass leaf blades(g)} + \text{petioles(g)}} \quad (1)$$

$$\text{Petiole porportion} = \frac{\text{Mass petioles(g)}}{\text{Total mass leaf blades(g)} + \text{petioles(g)}} \quad (2)$$

Then, we multiplied each proportion by leaf blade K conc/mass leaf blades + petiole K conc/mass petioles as follows:

$$\begin{aligned}\text{Whole leaf K concentration} = \\ (\text{Leaf blade proportion} \times \text{leaf blade K concentration}) \\ + (\text{petiole proportion} \times \text{petiole K concentration})\end{aligned} \quad (3)$$

While completing measurements, we observed that fruit K concentration changed with the type and length of fruit storage. Juice samples that were stored overnight in a cooler showed different K concentrations than the day before. Our capability to analyze fruit composition within a standard time period following sampling was limited due to our sampling criteria (i.e., on approximately the same date) and the large distances among vineyards. We were able to measure K concentration on samples from only five sites, as reported in Table S1. After samples were crushed and pressed with a potato ricer (without macerating seeds), 0.5 mL ionic strength adjustor was added to the juice (Orion ionplus Application Solution Potassium ISA ionic strength adjustor; Orion 931911), and then K was measured using an Orion Potassium Ion Selective Electrode (Thermo Fisher Scientific Inc, 2008).

At 17 sites, we collected 100-berry samples 1 or 2 days before commercial harvest. We pressed the fruit as before, centrifuged for 5 min at ~3500 rpm, and collected the juice supernatant. Brix was measured with a digital refractometer (Pocket PAL-1), and juice pH and titratable acidity were determined by titration to an endpoint of pH 8.2 and 0.1 N NaOH base using an 848 Titrino Plus autotitrator (Metrohm).

2.4 | Soil sample collection and processing

Nearly all soil samples were collected at the same time as veraison tissue samples, with a few samples collected at bloom (Table 1). We collected soil from 0 to 10- and 0 to 38-cm depths, since 0–10 cm is the recommended depth increment for no-till and pasture soil testing laboratory analyses

TABLE 1 Description of vineyard blocks/sites and their soil properties.

Vineyard location	Physiographic Province	Soil map unit	Parent material[a]	Number of blocks	Varieties and rootstocks
Afton, VA	Piedmont	Belvoir sandy loam	Colluvial and residual material weathered from crystalline rocks	3	Cabernet Franc, Merlot, Petit Verdot (RG)
Blacksburg, VA[b,c]	Ridge and Valley	Frederick and Vertrees gravelly silt loams	Residuum from a mix of shale, limestone, siltstone, and fine sandstone bedrock	2	Cabernet Franc, Merlot (101–14)
Burkittsville, MD	Ridge and Valley	Spoolsville-Catoctin complex	Loamy residuum weathered from greenstone	1	Cabernet Sauvignon (RG)
Crozet, VA	Piedmont	Dyke silt loam	Residuum weathered from greenstone	2	Petit Verdot (101–14)
Delaplane, VA[d]	Blue Ridge	Pignut-Alanthus complex	Residuum weathered from greenstone	2	Petit Verdot[f], Tannat (101–14)
Delaplane, VA	Blue Ridge	Pigeonroost-Edneytown complex	Residuum weathered from granite and gneiss	1	Cabernet Franc (RG)
Frederick, MD	Blue Ridge	Mt. Airy channery loam	Gravelly residuum weathered from low base phyllite and/or gravelly residuum weathered from low base schist	1	Chambourcin (101–14)
Front Royal, VA	Blue Ridge	Chester-Manor complex	Residuum weathered from granodiorite	1	Cabernet Franc[f] (101–14)
Hamilton, VA	Piedmont	Enon-Helena complex	Mafic rock residuum, granite gneiss residuum	3	Cabernet Franc, Landot Noir, Merlot (all 3309)
Keedysville, MD[e]	Ridge and Valley	Hagerstown silt loam	Residuum weathered from limestone bedrock	6	Petit Verdot[f], Cabernet Franc, Cabernet Sauvignon, Sangiovese, Teraldago, Chambourcin (all 101–14)
Landisville, NJ	Coastal Plain	Penn-Bucks complex	Residuum weathered from acid reddish shale, siltstone, and fine-grain sandstone	1	Merlot[f] (101–14)

(Continues)

TABLE 1 (Continued)

Vineyard location	Physiographic Province	Soil map unit	Parent material[a]	Number of blocks	Varieties and rootstocks
Leesburg, VA	Piedmont	Catoctin channery silt loam	Material weathered from basic crystalline rocks, including greenstone	2	Merlot[f] (101–14)
Madison, VA[c]	Piedmont	Eubanks-Lloyd loams	Residuum derived from mafic, igneous and high-grade metamorphic rocks.	3	Cabernet Franc[f], Merlot[f], Malbec[f] (all RG)
Mount Airy, MD	Piedmont	Brinklow-Blocktown channery loams	Residuum from micaceous crystalline rocks	2	Merlot[f], Petit Verdot[f] (RG)
Mount Airy, MD	Piedmont	Glenelg channery loam	Residuum weathered from mica schist	1	Merlot (101–14)
Mount Airy, MD	Piedmont	Mt. Airy channery loam	Gravelly residuum weathered from low base phyllite and/or gravelly residuum weathered from low base schist	1	Cabernet Franc (101–14)
Mount Airy, MD	Piedmont	Conestoga and Letort silt loams	Residuum mostly from micaceous limestone and calcareous schist	2	Chancellor (own), Marechal Foch
Mt. Crawford, VA[c]	Ridge and Valley	Berks-Weikert channery silt loams	Residuum of shale and siltstone	3	Petit Verdot[f], Cabernet Franc[f], Merlot[6] (all RG)
Ruther Glen, VA	Coastal plain	Kempsville-Emporia complex	Loamy marine deposits	2	Chambourcin, Cabernet Franc (101–14)

[a]Parent materials are from the major component of soil map unit (Soil Survey Staff, 2014).
[b]Very wet when sampling.
[c]Soil sampled at bloom.
[d]High cordon training.
[e]Replicated research vineyard, all 101–14 Mgt rootstock.
[f]Bloom petioles collected.

(Maguire & Heckendorn, 2011), whereas 38 cm is the approximate length of commonly used hand-held soil probes. We took at least 15 soil cores for each depth increment (i.e., 0–10 or 0–38 cm) randomly throughout vineyard blocks, collecting them into a clean bucket or large plastic bag. The soil cores were combined into composite samples that were then moist-sieved through a 2-mm sieve. Half of the soil samples were oven-dried to a constant weight at 25°C and the other half were stored at field-sample water content at 5°C. The change in mass of the oven-dried samples was used to calculate gravimetric water content of the moist samples.

2.5 | Soil extractions

We performed soil extractions in duplicates using three procedures: Mehlich 1, Mehlich 3, and NaTPB. We applied each method to subsamples representing all combinations of sample depth increments (i.e., 0–10 and 0–38 cm) and preparations (i.e., oven-dried vs. field-moist samples). The amount of soil added to each extraction was based on dry mass, so we corrected for moisture content. We measured gravimetric moisture content for each soil and then calculated the mass of moist soil equivalent to the mass of dry soil. For example, we extracted 6.5 g of moist soil at 30% gravimetric water content in order to process the soil at a dry equivalent of 5.0 g.

For Mehlich 1, we used a ratio of 5.0 g dry soil to 20.0 mL extractant (Maguire & Heckendorn, 2011; Mehlich, 1953; Mylavarapu et al., 2002). For Mehlich 3, we used 2.5 g dry soil to 25.0 mL extractant (Mehlich, 1984; Mylavarapu et al., 2002). For NaTPB extractions we used 1.0 g soil with 3.0 mL of extracting solution (0.167 M NaBPtu +1.7 M NaCl + 0.01 M EDTA), 25.0 mL of quenching solution (0.5 M NH_4Cl + 0.14 M $CuCl_2$; Cox et al., 1999; Rees et al., 2013; Wang et al., 2013; Wolf & Beegle, 2009). Each extracted solution was analyzed via ICP (ARCOS model Spectro Analytical Instruments; Habey et al., 1990; Maguire & Heckendorn, 2011).

2.6 | Data analysis

Results from ICP analysis were converted to mg/kg. We used JMP software for analysis (JMP, 1989). For the soils data, we created box and whisker plots to show distributions. We also subtracted dry K concentration from moist K concentration and graphed those distributions to determine if K was released or fixed by minerals during drying. Then, we completed simple linear regression analyses. First, we graphed distributions to check for normality. Then, we analyzed each soil combination (depth, moisture, and extraction) as the explanatory variable and each tissue type (bloom or veraison, petiole, leaf blade, and whole leaf) as the response variables. Since the moist samples were at different gravimetric water contents, we performed multiple regression analyses with gravimetric water content as an interaction term. As an example, we created a regression model with veraison petiole K concentration as the response variable and three explanatory variables: soil K concentration (Mehlich 1, 0–38 cm), soil gravimetric water content (%GWC), and the interaction term of soil K concentration × soil gravimetric water content. The final model for that combination had the following form:

$$\text{petiole } [K] = \beta_0 + \beta_1 (\text{soil } [K]) + \beta_2 (\%\text{GWC} \times \text{soil } [K]) + \varepsilon \quad (4)$$

3 | RESULTS

Measured K concentrations varied among the different soil depths, processing, and extractions (Figure 1). Most of the samples had K concentrations that were over the recommended maximum soil K concentration of 40 mg/kg (which assumes Mehlich 3 extraction). Samples from 0 to 10 cm typically had higher K concentrations than samples from 0 to 38 cm. NaTPB resulted in higher K extraction than Mehlich 1 or Mehlich 3, and Mehlich 3 generally showed higher K extraction than Mehlich 1.

Patterns of releasing or fixing K were inconsistent among sample depths and extraction solutions (Figure 2). Four samples had K differences of 0 ± 2 mg/kg between field-moist and air-dried samples. Another five samples had 5 mg/kg higher K concentrations in air-dried compared to field-moist conditions, indicating a small amount of released K. Of the remaining samples, two showed fixation of K and 16 showed release of K. Few samples from Blue Ridge and Coastal Plain physiographic provinces, all released K. In the Ridge and Valley, one sample fixed K, one neither released nor fixed, and three released K. In the Piedmont, one sample fixed K while 16 released K (Figure 2). At one vineyard in the Piedmont (Afton, VA), we sampled three individual vineyard sites, all within a square kilometer of each. Those sites showed differences of −7.82, 1.64, and 15.4 mg/kg in K concentration between air-dried and field-moist samples.

Analyses with all sites (including both French-American Hybrids and *Vitis vinifera* varieties) and with only *Vitis vinifera* varieties (excluding French-American Hybrids) showed similar results (Table S3). Soil samples from 0 to 38 cm better predicted tissue K concentrations than shallower samples (0–10 cm), with higher correlations between 0 and 38 cm samples and vine tissue K concentrations for every preparation and extraction except Mehlich 3 moist extraction (Table 2). Field-moist samples were better predictors of tissue K concentration than the corresponding dry samples for most analyses. For 0–38 cm sampled soils, Mehlich 1 better predicted K concentration than Mehlich 3 and NaTPB.

TABLE 2 Regression analysis results showing the strengths of relationships between soil potassium (K) concentration (as the explanatory variable) and tissue K concentration (as response variable).

	Bloom petiole (%K) versus				**Veraison petiole (%K) versus**			
	Soil K from 0 to 10 cm (mg/kg)		**Soil K from 0 to 38 cm (mg/kg)**		**Soil K from 0 to 10 cm (mg/kg)**		**Soil K from 0 to 38 cm (mg/kg)**	
	Moist	**Oven-dried**	**Moist**	**Oven-dried**	**Moist**	**Oven-dried**	**Moist**	**Oven-dried**
Mehlich 1								
R^2	0.0886	0.0655	0.314	0.387	0.150	0.0975	0.410	0.335
F-ratio	1.17	1.12	6.42	10.1	5.84	4.00	23.6	18.7
p value	0.30	0.30	0.024	0.0059	0.021	0.053	<0.0001	0.0001
Mehlich 3								
R^2	0.118	0.0158	0.128	0.350	0.169	0.0852	0.167	0.274
F-ratio	1.74	0.256	2.20	8.63	6.92	3.45	7.20	14.0
p value	0.21	0.62	0.159	0.0097	0.013	0.071	0.011	0.0006
NaTPB								
R^2	0.0621	0.195	0.186	0.209	0.202	0.194	0.354	0.295
F-ratio	0.926	3.88	3.21	4.22	8.86	8.91	19.2	15.5
p value	0.35	0.066	0.095	0.057	0.0052	0.0050	0.0001	0.0004
	Veraison leaf blade (%K) versus				**Veraison whole leaf (%K) versus**			
	Soil K from 0 to 10 cm (mg/kg)		**Soil K from 0 to 38 cm (mg/kg)**		**Soil K from 0 to 10 cm (mg/kg)**		**Soil K from 0 to 38 cm (mg/kg)**	
	Moist	**Oven-dried**	**Moist**	**Oven-dried**	**Moist**	**Oven-dried**	**Moist**	**Oven-dried**
Mehlich 1								
R^2	0.124	0.0514	0.278	0.180	0.245	0.104	0.615	0.534
F-ratio	4.68	2.00	13.1	8.12	5.85	2.43	32.0	24.0
p value	0.038	0.16	0.0010	0.0071	0.0264	0.13	<0.0001	<0.0001
Mehlich 3								
R^2	0.117	0.0360	0.0630	0.100	0.259	0.111	0.540	0.315
F-ratio	4.51	1.38	2.42	4.10	6.99	2.62	23.5	9.66
p-Value	0.041	0.25	0.13	0.050	0.016	0.12	<0.0001	0.0053
NaTPB								
R^2	0.0768	0.0432	0.122	0.0629	0.336	0.313	0.549	0.414
F -ratio	2.91	1.67	4.88	2.48	10.1	9.56	24.4	14.9
p value	0.097	0.20	0.034	0.12	0.0047	0.0055	<0.0001	0.0009

Note: Each combination of soil depth/moisture/extraction and tissue type/timings was analyzed separately. We report R^2 values as well as *F*-ratio values and *p*-values. Gray shading indicates relationships with $p < 0.05$.

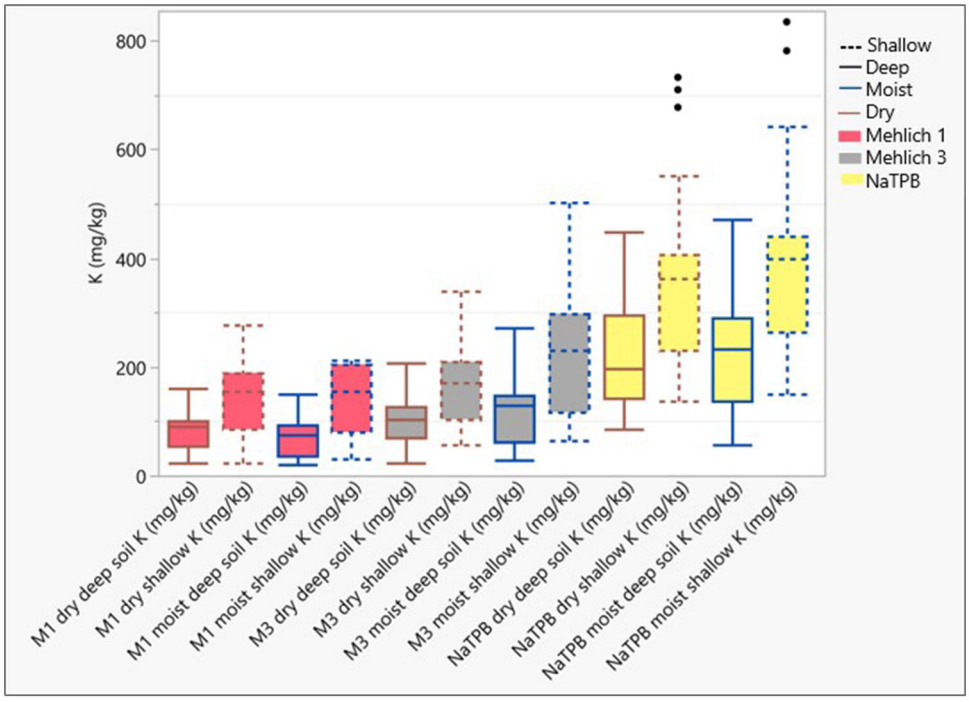

FIGURE 1 Measured potassium (K) concentrations from three chemical extractions (M1, Mehlich 1; M3, Mehlich 3; NaTPB, sodium tetraphenylboron), both depth intervals (shallow, 0–10 cm; deep, 0–38 cm), and both types of sample preparation (moist, field-moist; dry, oven-dried).

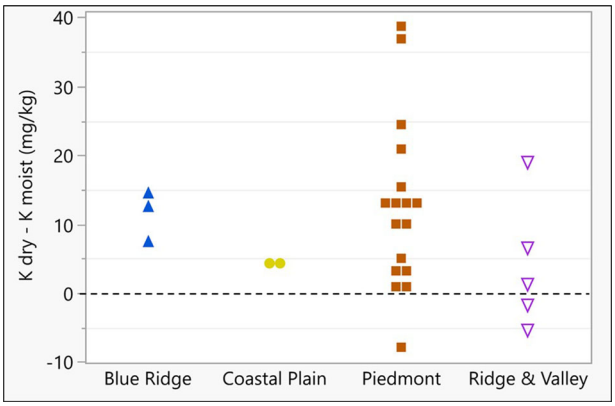

FIGURE 2 Differences in soil potassium (K) concentrations between oven-dried and field-moist samples, with data organized by physiographic province. These samples were collected from 0 to 38 cm and were analyzed using the Mehlich 1 extraction. The dotted line is at zero, indicating no difference between dry and moist extractions. Positive numbers indicate release of K when soils were dried while negative numbers indicate fixation of K when soils were dried.

Veraison whole leaf tissue sample K concentrations showed better relationships with soil K concentrations than petiole or leaf blade samples alone. Mehlich 1 extraction of moist soil from 38 cm was the strongest predictor of tissue K concentration ($R^2 = 0.615$). Adding soil moisture to the model did not improve the model in most cases (Table 3). The interaction term of soil moisture level with extraction was not significant for any combination of explanatory variables.

The limited fruit chemistry data (Table S1) that we successfully collected ($n = 17$) showed weak relationships between fruit pH and all tissue K concentration (Table S2). The strongest of the relationships with fruit pH was with veraison petiole K concentrations, which explained 27% of differences in fruit pH. Whole leaves predicted 19% of differences in fruit pH, veraison leaf blades predicted 5.6%, and bloom petioles predicted 5.2%.

4 | DISCUSSION

4.1 | Effects of sampling, processing, and extraction on soil potassium concentration

In this study we aimed to identify the best combination of soil sampling depth, sample preparation, and extraction method for predicting tissue K concentrations in wine grapes. We hypothesized that vines were accessing nonexchangeable K in the subsoil because of previously reported issues with high tissue K and the lack of correlations with soil tests (Beasley et al., 2017; Wolf, 2016). Based on this hypothesis, we expected Mehlich 3 and NaTPB to better predict tissue K because they would extract more nonexchangeable K than Mehlich 1. According to our data, both Mehlich 3 and NaTPB did extract more K than Mehlich 1. However, the Mehlich 1 extractions

TABLE 3 Results of multiple regression analysis for the field-moist soil samples. Response variables included veraison tissue types (petioles, leaf blades, and whole leaves)

	Mehlich 1 soil [K] (0–10 cm)	Mehlich 1 soil [K] (0–38 cm)	Mehlich 3 soil [K] (0–10 cm)	Mehlich 3 soil [K] (0–38 cm)	NaTPB soil [K] (0–10 cm)	NaTPB soil [K] (0–38 cm)
Veraison petiole (%K)						
β_0	1.57	1.35	2.38	3.47	2.52	2.09
$\beta_{\text{Soil[K]}}$	**0.012**	**0.028**	0.0056	0.012	**0.0048**	**0.013**
β_{GWC}	−0.014	−0.0091	−0.03	−0.085	−0.060	−0.090
$\beta_{\text{interaction}}$	0.00015	−0.0014	−0.00045	**−0.0025**	−0.00028	−0.00077
R^2 (adjusted of model)	0.172	0.255	0.113	0.160	0.150	0.256
Veraison leaf blade (%K)						
β_0	0.91	0.91	1.02	1.18	1.05	0.99
$\beta_{\text{Soil[K]}}$	**0.0018**	**0.0039**	0.00059	0.0013	0.00033	**0.0015**
β_{GWC}	−0.0099	−0.011	−0.00993	−0.018	−0.011	−0.017
$\beta_{\text{interaction}}$	0.00025	1.8e−5	2.4e−5	−0.00020	0.000031	−0.000017
R^2 (adjusted of model)	0.250	0.232	0.012	0.016	0.007	0.077
Veraison whole leaf (%K)						
β_0	0.74	0.13	0.48	0.024	0.66	0.32
$\beta_{\text{Soil[K]}}$	0.0023	0.0088	0.0015	0.0080	0.0016	0.0037
β_{GWC}	−0.0028	0.023	0.011	0.018	−0.0080	0.0042
$\beta_{\text{interaction}}$	−0.00035	−0.00022	−0.00034	5.2e−5	−4.3e−5	−0.00026
R^2 (adjusted of model)	0.290	0.238	0.066	0.148	0.063	0.138

Note: Explanatory co-variates included soil potassium (K) concentration, soil gravimetric water content (%GWC), and the interaction term soil K concentration × soil gravimetric water content. Beta values are reported for each model parameter, as are adjusted R^2 values for the whole model. Beta values in bold indicate significant values ($\alpha = 0.05$).

had the greatest correlations with plant-tissue K. This result suggests that vines may not be accessing as much nonexchangeable K as we thought, so we rejected our hypothesis that vine roots are accessing nonexchangeable K.

Our data provided evidence for the portion of the soil profile that vines use to access K. Samples collected from 0 to 38 cm samples were better correlated with tissue K concentration than 0–10 cm, implying that the vines are accessing K from deeper in the soil than is usually sampled. This response might also explain why some growers have found lack of correlation with soil tests that only analyze shallow samples. Grapevines have a greater proportion of deep roots compared to other woody plants (regardless of rootstock) and those roots tend to be most concentrated around 21–60 cm, which typical soil sampling does not reach (Ferlito et al., 2020; Smart et al., 2006). Currently, deep sampling of vineyard soils is only recommended before planting, when subsoil properties can still be altered (Wolf, 2008). Even so, subsoil properties are difficult to change, and our understanding of grapevine root architecture is incomplete, though we know that root morphology plays a role in K uptake, though there is a complex interaction with the scion variety (Kodur et al., 2010; Mpelasoka et al., 2003). Future research should investigate different sampling depths as well as specific varieties, clones, and rootstocks.

Our analysis also determined that the soil moisture content at time of extraction affected K concentrations. Field-moist samples had better correlations with tissue K than did air-dried samples. Other studies have similarly found that extractions of moist soils were better correlated with plant response than dried soils (Barbagelata & Mallarino, 2013; Luebs et al., 1956). One possibility for this result is that analyzing the samples under field-moist conditions minimized changes in K availability that can occur when certain clay minerals are dried. Our data indicated many discrepancies in soil K concentrations between air-dried and field-moist samples, with the majority of samples releasing K upon drying (n = 24 samples) and a few others fixing K (n = 3 samples). Both of these patterns are consistent with the disconnect between soil analysis results and tissue analysis results commonly observed by growers in this region.

We also identified some regional patterns in K release. In the Piedmont region 16 of the 17 soil samples released K on drying. There were not enough sites in the other regions to draw definitive conclusions, but the Ridge & Valley was the only other region with samples that indicated K fixation (n = 2). Although we did not quantify mineralogy on our samples, previous work has shown that soils high in illite are more likely to release K, whereas vermiculites tend to fix K upon drying (Dowdy & Hutcheson Jr., 1963). The study area

included a range of soil textures, mineralogies, and parent material, including widespread presence of illites and vermiculites. Granite, sandstone, gneiss, and other K-bearing rocks and minerals can also provide K (Manning, 2010). Similar mineralogies exist in many winegrape-growing regions of the world. Therefore, growers whose vineyards have such soils should strive to have moist samples analyzed.

Based on the above comparisons, it is likely that using dried samples for K analysis may over-estimate the amount of plant-available K. Therefore, recommendations based on dry soil samples may underestimate the need for K fertilizer, which is an unexpected finding. Most reports in the region have concluded that soil tests typically underestimate plant-available K, and therefore overestimate the need for K fertilizer, even when tissue K is high. One possibility here is that Mid-Atlantic soils may contain lower K concentrations than widely considered by growers, yet grapevines may be particularly adept at mining soil K due to a combination of factors including warm weather, moist soil conditions, and dense canopies. In this case, tissue analyses are an important companion to soil analyses. Still, those seeking to establish vineyards should attempt use a soil testing lab that will run moist samples, and future research should investigate different drying temperatures and levels of moisture, since analysis of moist samples can result in increased variability (Haby et al., 1990).

4.2 | Correlations between soil and plant-tissue potassium concentrations

Our data indicate that collecting relatively deep soil samples (0–38 cm) and analyzing the samples under field-moist conditions using Mehlich 1 extraction generally provided the best predictor of tissue K concentration (Tables 2). Extraction of oven-dried and relatively shallow (0–10 cm) samples generally were less suitable for predicting tissue K concentrations. As expected, K from moist samples almost always showed stronger relationships with tissue K concentrations than did dry samples (Table 2). Our multiple linear regression models also revealed that water content at time of sampling had little effect on predictions of tissue K, and that interactions between soil K concentration and water content at sampling were generally not significant. Growers and soil testing labs should not have to be concerned with the specific moisture content of samples, just that they are field-moist.

The data gave some indication of which types and timing of tissue sampling best correlated with soil K concentration. Veraison sampling showed stronger relationships with soil K than bloom sampling, which agrees with previous research and recommendations (Boynton et al., 1958; Wolf, 2008). The differences between tissue types at veraison were less clear. For the single linear regression analyses, soil K from 0 to 38 cm explained 54.0%–61.5% of differences in whole leaf K (depending on extraction method). The correlations with petiole K were much lower, ranging from 16.7% to 41.0%. The multiple linear regression analysis, by contrast, tended to have higher R^2 values between soil K and petiole K than between soil K and whole leaf or leaf blade K.

Previous research has investigated petiole and leaf blade sampling, but no known research has investigated whole leaf sampling in similar climates. Leaf blades are a sink for K whereas petioles are transport tissues, so sampling both together gives a snapshot of the nutrients being transported at that moment in time as well as the K accumulated in the leaf. As of 2022, only one known viticulture extension program recommends whole leaf samples, and their recommendation is at least partially because whole leaves are easier to sample (Washington State University; Moyer et al., 2018). A few programs recommend leaf blade samples, as supported by recent research on the US West Coast (Schreiner & Osborne, 2020; Schreiner & Scagel, 2017). In their study of K nutrition of Pinot Noir vines, Schreiner and Osborne (2020), compared leaf blades and petioles and found that leaf blade K was better than petiole K at predicting must (crushed fruit) pH and K. A few other research projects have analyzed whole leaves but have not compared to soil K or other tissue types (Arrobas et al., 2014; Melo et al., 2018). Therefore, our results suggest that whole leaf sampling may be a strategy that warrants further investigation for making nutrient management decisions. Until these results are corroborated by other work, however, we suggest that growers with established vineyards continue to focus on petiole samples for K management decisions, particularly if they already have past datasets of petiole analysis.

The current advice from Mid-Atlantic US Extension professionals and consultants is to base all K fertilizer decisions on tissue analyses (Wolf, 2016). Our results suggest that soil sampling may be a suitable substitute for tissue analysis if conducted with proper sampling depths and extraction methods. Nonetheless, there are limitations with these types of predictive analyses. Other variables such as the rootstock, variety, sunlight exposure of the canopy, and crop load can affect tissue K (Kodur et al., 2010; Mpelasoka et al., 2003). We also note that recommendations from other regions with high fruit pH issues focus on monitoring fruit pH as it ripens (Schreiner & Osborne, 2020). Given the variability of soils and the complexity of the soil-vine-atmosphere system, soil analysis may not be suitable for predicting potential fruit pH issues. Our results reflected this complexity, as we found only weak relationships between fruit pH and all soil or tissue K concentrations. These poor relationships are likely because fruit pH is affected by more than K. For example, acid accumulation and degradation in fruit are affected by crop level, vine size, rootstock, and fruit zone microclimate, including the level of fruit exposure to the sun. Potassium has a complex relationship with those factors and is usually corre-

lated with them; for instance, shaded fruit tend to accumulate more K and have higher pH (Kodur et al., 2010; Mpelasoka et al., 2003). Tissue analyses are nonetheless useful for important for diagnosing potential nutrient deficiencies or excesses.

4.3 | Conclusions and Future Work

The overarching goal of this project was to identify the best combination of soil sampling, handling, and analysis to predict tissue K in grape vines. Soil samples from 0 to 38 cm that were moist extracted with Mehlich 1 was the best predictor of tissue K concentration ($R^2 = 0.615$). The study demonstrated that many soil samples released K upon drying, while a few others fixed K, both of which could confound routine soil analyses. According to our results, moist extraction is a valid alternative to dry extraction since it (1) avoids the fixation/release of K and (2) better correlates with tissue K concentrations. We also determined that sampling soils from 0 to 38 cm had consistently better correlations with tissue K concentrations than 0–10 cm samples. Thus, deeper than typical soil sampling may better be suited to predict tissue K. Mehlich 1 extraction (of moist, 0–38 cm) showed the best relationship with veraison whole leaf samples, but other extraction types also had strong relationships with tissue K. Future efforts should test different depths, moisture levels, and sampling timings.

Our results support the use of soil K analysis when making fertilizer decisions, but this recommendation comes with several caveats. First, the best correlations with soil K with tissue samples were collected at veraison. This timing occurs after most plant uptake of K has occurred, meaning that it is often too late to implement amelioration strategies. Therefore, K management should be considered a multi-year effort, with soil sampling representing a valuable tool for long-term nutrient management. Second, we observed relatively weak correlations between fruit pH and plant tissue K ($R^2 < 0.026$). This result emphasizes the challenges with monitoring and managing fruit pH based on soil or tissue K. Nonetheless, tissue K analyses are important for making proper fertilization decisions and identifying soils that may be supplying insufficient or excess K.

Taken altogether, our findings are a step towards a better understanding of K availability to grapevines in the Mid-Atlantic US region and similar regions around the world. This information should help growers better collect samples for soil K evaluation, and can inform their management decisions when establishing or managing vineyards. Knowing the soil K of a vineyard site before establishment can help growers choose rootstocks, varieties, and training system. In established vineyards, soil sampling can help inform management decisions (such as choosing to remove leaves or crop thin). This information should also allow soil testing labs to better serve grape growers with more accurate testing methods, and ultimately help refine soil management and fertilizer recommendations to optimize wine quality in the Mid-Atlantic United States and other growing regions with similar climate and soils.

AUTHOR CONTRIBUTIONS

Jaclyn C. Fiola: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; visualization; writing–original draft. **Ryan D. Stewart**: Conceptualization; funding acquisition; investigation; project administration; resources; supervision; writing–review and editing. **Greg K. Evanylo**: Conceptualization; funding acquisition; methodology; resources; supervision; writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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