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Considerations with soil testing in turfgrass

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1 Introduction

Soil testing can be a valuable method to help turfgrass managers make fertilizer decisions and choosing the most appropriate soil test extractant is key. This depends on soil properties and the availability of correlation data for turfgrass species in the desired region. This chapter describes common extracts and demonstrates their efficacy for phosphorus (P) and potassium (K) extraction with three soil samples from the North American Proficiency Testing program (www.naptprogram.org) administered by the Soil Science Society of America (Madison, WI, USA). Fertilizer recommendations were made based on regional sufficiency levels from university soil-testing laboratories and the Minimum Levels for Sustainable Nutrition (MLSN) guidelines from the Asian Turfgrass Center (www.asianturfgrass.com; Bangkok, Thailand) and PACE Turf (www.paceturf; San Diego, CA). Sufficiency Levels for Available Nutrients (SLAN) or MLSN guidelines are considered the most appropriate for deciding how to fertilize the turf. However, recommendations based on an inappropriate extractant, calibration, saturated paste extraction, or ideal ratios of major exchangeable cations (i.e. Basic Cation Saturation Ratio; BCSR) are considered inappropriate.

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2 Soil testing

Obtaining a soil test and resulting fertilizer recommendations is based on a three-step process of 'correlation,' 'calibration,' and 'interpretation' (Brown, 1987; Hopkins, 2020). To start, the soil sample is mixed with a liquid solution varying in composition and concentration, with the resultant solution then containing extracted soil nutrients. The concentration of nutrients in the solution varies with a wide range of factors, including extractant properties, sample shaking time, relative ratio of soil-to-solution, and shaking method (i.e. orbital, speed, etc.). After extraction and filtering, the supernatant is analyzed (another entire topic of research) for various nutrients of interest. The amount of extracted nutrient should correlate well with plant nutrient uptake, yield, or another factor of interest, such as turfgrass color or density. Calibration is the process of determining crop response, over a range of soil-test result values (Mitchell and Mylavarapu, 2014). Ideally, calibration must be conducted for different crops and in different soil types and geographic regions. In many cases, we are missing key calibration data for turfgrasses. This is true for newer turfgrass species of interest, such as seashore paspalum, or for commonly utilized turfgrass species that may be managed differently by geographic region, such as annual bluegrass. A final step in the soil-testing process is interpretation, where a fertilizer recommendation is provided based on soil-test results as related to soil-test calibration data.

First, a soil sample is removed (a typical sampling depth is around 8–10 cm for turfgrass) and sent to a soil-testing laboratory. In the laboratory, the soil is air dried, pulverized, and extracted with a solution known to remove a nutrient amount that correlates well with plant growth. Often, the same extractant is used to remove several nutrients, as a single extractant that works well for multiple nutrients is more efficient than having to analyze a soil with numerous extractants. Fertilizer recommendations are then made based on available, extractant-specific calibrations of nutrient concentrations to crop responses.

There are plant nutrients for which we lack this correlation, calibration, and interpretation. The most common of these is nitrogen (N), which is readily leached or lost to the atmosphere from the soil, thus making it difficult to correlate with season-long needs for turfgrass and other crops. To overcome this problem, fertilizer recommendations for N are based on years of crop response testing, determined from years of application of N to various crops across a wide range of soil types and climates. Other plant nutrients for which we lack widely useful calibrations include sulfur (S) and most of the micronutrients.

2.1 Soil test extractants

Knowledge of basic soil types allows a turfgrass manager to best manage their soil and rootzones, including activities that vary with soil type, such as

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cultivation, fertilization, and establishment. Obtaining a soil test is one of the first activities for the management of a turfed soil. Results of that soil test can vary with many factors, and soil type or rootzone is a major one. This subsection will discuss the common soil test extractants used in the USA and how soil-test results may vary with soil and extractant type.

2.1.1 Bray P1

The Bray P1 extractant is primarily used to measure soil P. The Bray P1 soil test, which was developed in 1945 (Bray and Kurtz, 1945), uses fluoride in dilute acid to extract a proportion of soil P. More commonly used in the north central USA than in the south or west, this extractant is reliable on neutral or acid pH soils (Mallarino, 1995) and will underestimate plant-available P in calcareous soils (alkaline pH soil with excess carbonates). Most soil-testing laboratories in the north central region of the USA (except North and South Dakota, where soils are largely calcareous) use the Bray P1 extractant (Frank et al., 2011). It is also listed as a suitable extractant for other acid to neutral pH soils, even those in the western USA (Gavlak et al., 2005). In acidic soils, extraction with the Bray P1 and Mehlich 3 extract give nearly identical P concentrations that are strongly correlated when the extracts are analyzed via a colorimetric method. If Mehlich 3 extracts are analyzed using Inductively Coupled Plasma (ICP) as the analytical equipment, P concentrations from the Mehlich 3 extract will be greater than those measured with the Bray 1 extracts. However, they are still very strongly correlated (Pittman et al., 2005).

2.1.2 Bray P2

The Bray P2 extractant is more strongly acidic than the Bray P1 extractant, which means it will extract more P from the soil. Some soil-test reports will provide both Bray P1 and Bray P2 results, with the Bray P2 accounting for less soluble forms of P. However, most fertilizer recommendations for P do not consider the Bray P2 extractant because it does not correlate as well as Bray P1 or Mehlich 3. In some work, soil P extracted by Bray P2 was about twice that extracted by the Mehlich 3 extract (Wang et al., 2004).

2.1.3 Mehlich 1

Mehlich 1 is also known as the double acid extractant. This method was originally introduced by Dr. Mehlich in 1953 to determine the availability of P, K, calcium (Ca), and magnesium (Mg) (Mylavarapu and Miller, 2014). Additionally, boron (B), sodium (Na), copper (Cu), zinc (Zn), and manganese (Mn) can be extracted using Mehlich 1. However, S cannot be determined by Mehlich 1 because the extractant itself contains sulfur (sulfuric acid; H_2SO_4). Mehlich 1 is not a suitable P extractant from neutral or alkaline soils, or where apatite is the predominant source of plant-available P. Alkalinity neutralizes the effectiveness of dilute acids, therefore P will be under-extracted in alkaline soils. In the southeastern region of the USA, five states use the Mehlich 1 extractant (Hanlon, 2007), primarily on acidic and sandy soils.

2.1.4 Mehlich 3

Mehlich 3 was introduced in 1984 (Mehlich, 1984). The Mehlich 3 test includes fluoride to prevent P from re-precipitating with aluminum (Al) (Zhang et al., 2014). A chelate (ethylenediaminetetraacetic acid; EDTA) was also added for better extraction of micronutrients. Additionally, Dr. Mehlich replaced hydrochloric acid and H_2SO_4 with nitric acid to help extract calcium phosphate and added acetic acid to buffer the solution to a pH of 2.5 and minimize the solution from being neutralized in alkaline soils. The Mehlich 3 extractant is considered to be widely effective and works well over a wide range of nutrients, soils, and soil pHs. As such, it often is considered a 'universal' extractant. It is specifically mentioned for use in the southeastern USA (Hanlon, 2007) and for the extraction of P in northeastern soils where P availability is largely controlled by aluminum phosphates (Wolf and Beegle, 2011). In addition to extracting soil P, it is often used to extract other nutrients, including K (Watson and Mullen, 2007), Ca and Mg (Wolf and Beegle, 2011), Na, and micronutrients (Sawyer and Mallarino, 1999).

In the southeastern USA, various states use Mehlich 1 for extractable P and K, and others use Mehlich 3 for those same nutrients. As such, the relationship between these two extractants has been studied, and various conversion equations between the two are available (Sikora et al., 2005). The various conversion equations are state-specific, or they were developed as part of the North American Proficiency Testing program (NAPT), which is a quality program for soil-testing laboratories to check their accuracy for the various analytical tests they perform (Soil and Plant Analysis Council, 2000).

2.1.5 Olsen (sodium bicarbonate)

Olsen (sodium bicarbonate) or the Olsen P test ('Olsen') is considered the primary extractant for use in neutral to alkaline soils (Olsen et al., 1954; Wolf and Baker, 2008). In the Pacific Northwest and Northern Great Plains regions of the USA, the extractant is also used to measure plant-available K, nitrate, and S.

The Mehlich 3, Bray P1, and Olsen extracts are three of the most widely used soil extractants, and so comparisons have been made between the relative pools of P (or other nutrients) that they remove (Hopkins and Hansen, 2019). In general, results from the use of the Bray P1 and Mehlich 3 tend to be similar in acid soils, and equations documenting their close linear relationship for soil P extraction (albeit in limited crops and soils) exist (Eckert and Watson, 1996). In calcareous soils (soil pH >7.4), the Olsen extractant is generally recommended as the Bray P1 and, possibly, the Mehlich 3 test will yield incorrectly low P values. The reverse is true in acid soils (soil pH <5.0), a situation where the Olsen extract is not generally recommended (Sawyer and Mallarino, 1999).

2.1.6 Morgan

The Morgan (sodium acetate, pH 4.8) and modified Morgan (ammonium acetate, pH 4.8) extractants are used primarily by soil-testing laboratories not only in the northeastern USA but also in a few other locations. The Morgan test was developed as a 'universal' extractant for acid soils, with the single extractant used for P, Ca, Mg, and K, and, with the use of the modified Morgan, for micronutrients.

The Morgan methods often extract a smaller amount of nutrients than other methods (e.g. Bray). There are equations that quantify the relationship between extracted nutrients via the Mehlich 3 and Morgan methods (Ketterings et al., 2001a,b, 2002). This extractant is not commonly used outside the northeastern USA.

2.1.7 Lancaster

Lancaster (i.e. the Mississippi soil test method) is a soil test extractant developed for both the acid and alkaline soils of Mississippi where it is used for P, K, Ca, and Mg analyses (Oldham, 2014; Hanlon, 2007). It is not widely used outside Mississippi.

2.1.8 Ammonium acetate (1 M NH_4OAc)

The ammonium acetate (1 M NH_4OAc) extractant may be used to determine K, Ca, Mg, and/or Na in soils, especially in calcareous soils (Warncke and Brown, 2013). Two issues with this extractant are that it is not effective in saline or sodic soils (a pretreatment is needed), and the method does not account for free carbonates or gypsum (Gavlak et al., 2005). As it is an extractant for exchangeable cations, results from NH_4OAc extraction are sometimes used for the determination of cation exchange capacity (CEC) (Warncke and Brown, 2013).

2.1.9 Diethylenetriaminepentaacetic acid (DTPA)

Diethylenetriaminepentaacetic acid (DTPA) is a chelating agent which is sometimes used for the extraction of micronutrients (e.g. Fe, Mn, Cu, Zn) from soil (Whitney, 1998). B is the exception and is usually quantified via a hot-water extraction. However, many soil-test laboratories that use a general extractant such as Mehlich 3 or ammonium acetate will not use DTPA (or hot water) for micronutrients, and micronutrients are measured from the general supernatant.

2.1.10 Monocalcium phosphate

Recently, plant responses to added S have become more commonly observed, and have been documented in cotton and corn. This response is likely related to the improvement of air quality in the USA, and the subsequent reductions in S deposition. Sulfur soil tests, and correlation and calibration to various crop responses, are not especially well developed, and so if an S soil test result is reported it is often due to a general extractant such as Mehlich 3. However, the use of monocalcium phosphate may be a better-calibrated extractant for S (Singh et al., 2011), although research in this area is limited.

2.1.11 Saturated paste extract

Saturated paste extract (SPE) is created by saturating a soil sample with distilled water and allowing it to sit for as many as 8 h, after which the supernatant is suctioned off for analysis (Warncke, 2014). SPE is often used for soilless potting mixes and media or to determine if soils in arid parts of the USA are saline, saline-sodic, or sodic.

Soilless media have very low to no mineral soil content, thus, there are few to no reactive minerals such as iron (Fe)- and Al-oxides on which other minerals adsorb. Therefore, most of the nutrients present in soilless media are soluble and found in the media extract. When mineral soil is added to these substrates, nutrients that adsorb to mineral soil are not extracted and SPE will underestimate the nutrient supplying power of the mix. This phenomenon sometimes emerges as a topic in the popular turfgrass science literature where SPE is incorrectly interpreted as a measure of plant-available nutrients. However, it is critical to reiterate that a SPE does not extract nutrients that have the potential to become plant available over a growing season (i.e. those on the CEC sites or less soluble forms). Rather, SPE only measures elemental intensities as they relate to and affect salinity, not the quantity that will affect the nutrition of a plant. This mild, water-based extract is thus not useful for determining soil nutrient levels over a period of plant growth and therefore is not well calibrated to fertilizer recommendations (Carrow et al., 2003).

When SPE is used to determine soil pH, electrical conductivity (ECe), solution concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, B, HCO_3^-, CO_3^{2-}, SO_4, sodium adsorption ratio (SAR), or exchangeable sodium percentage (ESP) ratio, the soil

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must also be analyzed for nutrients using appropriate extractants (i.e. Olsen P, ammonium acetate, or DTPA) for typical soils of the western USA.

2.2 Soil test calibration and the basis for fertilizer recommendations

Thus, a soil test provides some measure of plant nutrient content in the soil. Soil test calibration places the soil-test results into categories, upon which the likelihood of a plant response is based (Dahnke and Olson, 1990). Typically, those categories are something like 'Very Low,' 'Low,' 'Medium,' 'High,' and 'Very High,' and the fertilizer nutrient would be recommended at any soil test result below 'Medium,' as a crop response to that added nutrient would likely be observed. The point at which a soil test result moves from 'Medium' to 'High' is determined, in general, by two different concepts: (1) SLAN or (2) BCSR (Eckert, 1987). There have been many adjustments and small alterations to these two fundamental concepts. It is important to know that each method exists because both are used in the turfgrass industry and either may be manipulated, or unintentionally misused with good intentions, to encourage increased use of fertilizers. Typically, the SLAN concept is used more widely for determining fertilizer recommendations for turfgrass.

There is newer research that proposes a new calibration method for K, P, Ca, Mg, and S in turfgrass: MLSN (Stowell and Woods, 2013; Woods et al., 2014). The method was created from a large data set (16 163 soil samples collected voluntarily by turfgrass practitioners worldwide) from sites with good turfgrass performance at sample collection. The data were filtered to include only soil samples with pH 5.5–8.5 (to avoid the factors of Al toxicity and alkalinity hazard) and with total CEC < 6 $cmol_c \cdot kg^{-1}$ (to select for samples where turfgrass was performing well in low nutrient content soils). The resulting 3683 soil samples were fit to a log-logistic model to identify, for each nutrient, the concentration where 10% of soil samples from the data set would have a lower nutrient concentration (and 90% would have a greater nutrient concentration). In other words, the MLSN sufficiency levels represent the 10th percentile nutrient concentrations from the data – again, where the turfgrass at the site was performing well. These guidelines (i.e. to withhold fertilizer of each nutrient unless K < 37 $mg \cdot kg^{-1}$, P < 21 $mg \cdot kg^{-1}$, Ca < 348 $mg \cdot kg^{-1}$, Mg < 47 $mg \cdot kg^{-1}$, or S < 7 $mg \cdot kg^{-1}$) are becoming increasingly popular in the turfgrass industry.

Currently, most public soil test laboratories base their fertilizer recommendations upon the SLAN concept, which states that there is some given nutrient level in the soil above which the crop will not respond, even if more of that nutrient is supplied. For many of our crops that response is the yield of the edible portion of the plant, and, at some soil-test level, the sufficiency level concept indicates that adding more of a nutrient will no longer increase

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crop yield. Of course, for turfgrass, the response can be a variety of indicators, including color, density, clipping yield, ball roll, abiotic or biotic stresses, or some other measure of turfgrass performance.

The BCSR does not focus on given levels of nutrient sufficiency but instead focuses on ideal ratios or proportions of the major exchangeable cations (typically, K, Mg, and Ca) (Dahnke and Olson, 1990). The originally proposed ranges (from the 1940s) were 65–75% Ca, 10% Mg, 2.5–5% K, and 2–10% H, with approximate ratios of 7:1 Ca:Mg, 15:1 Ca:K, and 3:1 Mg:K (Bear et al., 1945). Such ratios have been adjusted, fixed, and studied over many years. However, the overwhelming conclusion by many soil fertility experts is that there is little evidence to support the use of such ratios for fertilizer recommendations (Eckert and McLean, 1981; Rehm and Sorensen, 1985; Kopittke and Menzies, 2007; Chaganti and Culman, 2017). Further, recommendations for nutrients other than K, Mg, and Ca – such as P – typically come from SLAN guidelines. Last, even if the ratio of the cations in the soil is thought to be 'optimum,' a nutrient deficiency could still exist, especially in sandy soils with low organic matter content – a common situation for constructed turfgrass soils and rootzones such as putting greens and athletic fields. A brief comparison of SLAN, MLSN, and BCSR is available in Table 1.

Table 1 A brief comparison of common methods for interpreting soil nutrient tests for fertilizer recommendations

	Sufficiency levels for available nutrients (SLAN)	Minimum levels for sustainable nutrition (MLSN)	Basic cation saturation ratio (BCSR)
Relationship with soil nutrient test results	Assumes there is a concentration for each nutrient above which turfgrass will not respond to additional fertilizer	Assumes there is a concentration for each nutrient above which turfgrass will not respond to additional fertilizer	Assumes there is an ideal ratio of major exchangeable cations (i.e. K, Ca, and Mg) in soil
Calibration and interpretation	Based on field correlations among nutrient levels and turfgrass performance over a range of soil nutrient concentrations	A calibration of SLAN ideology to determine minimum sufficiency levels from a large number of low CEC soil samples from good-performing turfgrasses (over a range of species and geographies)	Only used to balance the ratio of K, Ca, and Mg SLAN or MLSN would be used for other nutrients, such as P
Considerations	Local calibrations for specific turfgrass species and soils are best	The same sufficiency levels are used regardless of turfgrass species, location, or geography	K, Ca, and Mg fertilizer recommendations are made regardless of their absolute concentration in soil

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3 A case study in sustainable soil test interpretation

3.1 Rational

Soil test extraction procedures and calibration for soil fertility recommendations vary greatly across the USA and can differ even between border states. Therefore, a soil sample submitted to different laboratories in neighboring states may produce different results and different soil fertilizer recommendations. This does not mean that one of the laboratories is producing incorrect results or recommendations, it is simply variation due to the extractant and/or calibration.

The objective of this case study is to highlight the influence of soil test extractions on soil test results as well as the impact of using different soil extractants with different soil test fertility recommendations for cool-season turfgrasses on putting greens (generally qualified as 'high maintenance') from around the USA.

3.2 Sample selection and description

To demonstrate the impact that soil test extraction methods have on results from different soils, three soils were selected from the NAPT (www.naptprogram.org), which is administered by the Soil Science Society of America. The soils selected from the database represented soils with low levels of P and K from three geographic regions (Mid-Atlantic, Midwest, and Southwest) to represent different combinations of physical and chemical properties of soils. The NAPT database is comprised of soil test results from public and private agricultural laboratories using common soil tests on homogenized soil samples collected from around the United States (NAPT, 2021). Consequently, the NAPT database allowed us to demonstrate the influence of different extraction methods on P and K results for the soils selected. Furthermore, by comparing NAPT data to state soil test laboratory recommendations in each region, we were able to compare the effects of interpretations of calibrations from each laboratory, which may vary based on turfgrass response to soil type and environmental conditions.

The chemical characteristics of the selected samples in Table 2 demonstrate the importance of understanding how extractants affect soil-test results. Because the relative extraction efficiency of the extractants used under different combinations of physical and chemical properties is known, the variability within samples in Table 2 is expected and hence regionally preferred extractants have been identified. It is critical for turfgrass managers to be familiar with the most suitable extractant(s) for their region to prevent misinterpretation of soil-test reports. This is less challenging when local laboratories are used because university soil-testing labs, for example, default to their regionally appropriate extractants and local turfgrass response calibrations. However, if soil samples

Table 2 Example of chemical characteristics of soils from Texas, Pennsylvania, and Illinois (USA) utilizing different soil extractants for phosphorus and potassium. Data were selected from the North American Proficiency Testing program (http://www.naptprogram.org/), which is administered by the Soil Science Society of America (Madison, WI, USA). Regionally common phosphorous (P) and potassium (K) extractants are shaded by the sample

	Texas	Pennsylvania	Illinois
	pH		
Soil pH (1:1)	7.1	6.0	5.8
	Extractable P ($mg \cdot kg^{-1}$)		
Bray P1 (1:10)	68	26	20
Bray P2 (1:10)	79[a]	32	26
Mehlich 1	59	12	16
Mehlich 3	77	36[a]	27[a]
True Morgan	27	2[b]	4[b]
Olsen	22[b]	12	13
Upper quartile	*78*	*33*	*26*
Median	*64*	*19*	*18*
Lower quartile	*26*	*10*	*11*
	Extractable K ($mg \cdot kg^{-1}$)		
Ammonium Acetate	41	97	113
Mehlich 1	35[b]	74[b]	74[b]
Mehlich 3	45	99	114[a]
Olsen	41	107[a]	105
Bray P1	49[a]	83	89
True Morgan	36	82	89
Upper quartile	*46*	*101*	*113*
Median	*41*	*90*	*97*
Lower quartile	*36*	*80*	*85*
	Cation Exchange Capacity ($cmol_c \cdot kg^{-1}$)		
Estimate CEC	4	11	13

[a]Maximum extractable P or K within a sample.
[b]Minimum extractable P or K within a sample.

are submitted to a distant laboratory, a turfgrass manager should request only the most appropriate extraction method (and, preferably, locally developed SLANs for the extractant) to reduce misinterpretations.

To illustrate the range and variability of extractants on our selected soil samples, some descriptive statistics are also provided in Table 2. Extractable nutrient concentrations are shaded for extractants most suitable for the region of sample origin. Median extractable P ranged from 18 $mg \cdot kg^{-1}$for the Illinois sample to 64 $mg \cdot kg^{-1}$ for the sample from Texas and varied by up to 57 $mg \cdot kg^{-1}$

for extractants within a sample. The Texas sample had the largest interquartile range (52 mg·kg^{-1}) and varied the most among extractants. Median extractable K ranged from 41 mg·kg^{-1} for the Texas sample to 97 mg·kg^{-1} for the sample from Illinois and varied by up to 40 mg·kg^{-1} for extractants within a sample. Interquartile ranges were smaller among K extractants within each sample and the Illinois sample varied the most with an interquartile range of 28 mg·kg^{-1}.

It is important to note that neither aligning with the median, extracting the minimum, nor extracting the maximum nutrient concentration indicates the best extractant for a sample because of the known relationships among extractants and soils. The nutrient extracted from a sample must correlate with turfgrass performance under the present soil conditions, which is the basis of selecting regionally preferred extractants and calibrating ranges to plant nutrient sufficiency levels. For example, the Mehlich 3 extractant is widely used throughout the USA and extracted the most (or nearly the most) P and K across our three samples. This is a meaningless fact unless the Mehlich 3 SLANs, and preferably local Mehlich 3 SLANs, are available for the origin of the sample. Alternately, turfgrass managers can use generalized SLANs such as the MLSN, which, because of relatively low sufficiency levels, often reduces fertilizer use compared to other recommendations.

3.3 Sufficiency levels and recommendations

The next step is to compare extractable P and K from each sample to sufficiency ranges for regionally appropriate extractions. Table 3 contains categories of P and K soil ratings correlated to extractants for state laboratories from select universities across the USA. MLSN sufficiency levels also are included. Note differences in sufficiency levels among laboratories using the same extractant, which demonstrates local calibration of the appropriate extractant and turfgrass performance.

3.3.1 Phosphorous

Beginning with the sample from Texas, the Mehlich 3 or Olsen extractants would be considered appropriate (77 or 22 mg·kg^{-1} extractable P, respectively) (Table 2). Because of the neutral pH of the Texas sample, the Mehlich 3 extractant is preferred over Olsen – especially since soil ratings from Texas A&M University ('Texas A&M'; College Station, TX, USA) used Mehlich 3. A Mehlich 3 level of 77 mg·kg^{-1} extractable P is considered 'High' (or 'Above Optimum') for Pennsylvania State University ('Penn State'; University Park, PA, USA) ratings (>75 mg·kg^{-1}), 'High' for University of Florida (Gainesville, FL, USA) ratings (>45 mg·kg^{-1}), 'High' for Texas A&M ratings (50–200 mg·kg^{-1}), and 'Sufficient' for MLSN ratings (>21 mg·kg^{-1}), resulting in the recommendation for 1 pound P_2O_5 per 1000 square feet (49 kg P_2O_5 per hectare) from the Penn State calibration, and no P fertilizer recommended from the University of Florida, Texas A&M, or MLSN calibrations (Tables 3 and 4). In this case, the Mehlich 3 soil calibrations from Penn State seem to overestimate the amount of P needed for a turf grown in Texas.

North Dakota State University ('North Dakota State', Fargo, ND, USA) and Utah State University ('Utah State', Logan, UT, USA) provide ratings based on the Olsen extractant. For 22 $mg{\cdot}kg^{-1}$, both North Dakota State and Utah State ratings for the Texas sample would be 'Medium' (13–28 and 16–30 $mg{\cdot}kg^{-1}$, respectively), resulting in recommendations for applications of 2 pounds P_2O_5 per 1000 square feet and 0 pounds P_2O_5 per 1000 square feet, respectively (98 kg P_2O_5 per hectare and 0 kg P_2O_5 per hectare, respectively) (Table 4). The former case again overestimating the amount of P fertilizer when compared to local recommendations. Though not typically recommended for Texas, ratings for Bray 1 and Mehlich 1 extractions were considered 'Very High' and 'High' based on calibrations from Kansas State University ('Kansas State', Manhattan, KS, USA) and Clemson University ('Clemson', Clemson, SC, USA), respectively, which also would result in no fertilizer recommendation. Note, however, that there are scenarios where mixing results and ratings from different extractants would, incorrectly, indicate the Texas sample was low in P. For example, the Olsen test result of 22 $mg{\cdot}kg^{-1}$ would yield 'Medium' soil ratings for all labs except Kansas State (Bray 1) and would be just above the sufficiency level indicated by the MLSN, the most frugal method.

Mehlich 3 is considered the most suitable extractant for Pennsylvania, for which the sample in this case study had 36 $mg{\cdot}kg^{-1}$ extractable P (Table 2). This result would receive a rating of 'Medium' (or 'Below Optimum'), 'Medium', 'Medium', and 'Sufficient' based on the Mehlich 3 soil ratings from the Penn State, the University of Florida, Texas A&M, and the MLSN, respectively, yielding recommendations for applications of 2.0 pounds P_2O_5 per 1000 square feet and 0.2 pounds P_2O_5 per 1000 square feet (98 kg P_2O_5 per hectare and 10 kg P_2O_5 per hectare) from Penn State and University of Florida laboratories, respectively (Table 4). Mehlich 3 calibrations from other labs do not indicate a need for P fertilizer. Since Penn State is the local lab in this case, it seems that P fertilizer is needed for our Pennsylvania sample and calibrations from other states have underestimated the amount of P needed by turf in Pennsylvania. Other extractants are not widely used or recommended for Pennsylvania but note that results from the Bray 1 extraction would yield fertilizer recommendations based on University of Wisconsin (Madison, WI, USA) and Kansas State calibrations, as would the Olsen extraction based on North Dakota State and Utah State calibrations and Utah State calibrations and the Mehlich 1 extraction based on Clemson calibrations.

The Bray P1, Bray P2, and Mehlich 3 extractants are most suitable for P extraction in Illinois, for which our sample had 20 $mg{\cdot}kg^{-1}$, 26 $mg{\cdot}kg^{-1}$, and 27 $mg{\cdot}kg^{-1}$ extractable P, respectively (Table 2). University of Wisconsin ratings

Table 3 General sufficiency levels, unless otherwise stated, for soil phosphorus (P) and potassium (K) from various labs and the Minimum Levels for Sustainable Nutrition (MLSN)

Soil rating level	Pennsylvania State University[a]	Clemson University	University of Florida	University of Wisconsin	University of Wisconsin	Kansas State University	Texas A&M University	North Dakota State University	Utah State University	MLSN
	Soil Extractable P ($mg \cdot kg^{-1}$)									
	Mehlich 3	Mehlich 1	Mehlich 3	Mehlich 3[b]	Bray P1[b]	Bray P1	Mehlich 3	Olsen P	Olsen P	Mehlich 3
Very low	–	–	–	0–5	0–12	0–5	–	0-6	<5	–
Low	–	<15	<25	6–10	13–25	6–10	0–20	7–12	5–15	–
Medium	<45	16–30	26–45	11–19	26–37	10–20	20–50	13–28	16–30	–
Sufficient	45–75	31–40	–	20–30	38–50	–	–	–	–	21
High	>75	41–60	>45	–	–	20–50	50–200	>29	31–50	--
Very High	–	–	–	>30	>50	>50	–	–	>50	–
Excessive	–	>60	–	–	–	–	–	–	–	–
	Soil Extractable K ($mg\ kg^{-1}$)									
	Mehlich 3	Mehlich 1	Mehlich 3	Bray P1[b]	Bray P1[c]	Ammonium acetate	Mehlich 3	Olsen	Ammonium acetate	Mehlich 3
Very low	–	–	–	0-50	0-20	0–40	–	0–40	<75	–
Low	–	<35	<35	51–100	21-40	41–175	0-75	41–175	76–125	–
Medium	<180	36–78	36–60	101–150	41-60	175–250	75–125	175–250	126–400	–
Sufficient	180–220	79–91	–	151–175	61–80	–	–	–	–	37
High	>220	92–118	>60	–	–	250–300	125–250	250–300	>400	–
Very high	–	–	–	>175	>80	>300	–	>300	–	–
Excessive	–	>118	–	–	–	–	–	–	–	–

[a]Pennsylvania State University uses 'below optimum,' 'optimum,' and 'above optimum' rating scale. The 'below optimum' corresponds to 'very low,' 'low,' and 'medium,' 'optimum' corresponds with 'sufficient,' 'high,' 'very high,' and 'excessive' corresponds with 'above optimum.'
[b]Interpretations specific to golf course turf.
[c]Interpretations specific to general turf areas, excluding golf turf.

Table 4 Phosphorus fertilizer recommendations from different laboratories utilizing frequently used soil extractants for soil samples from three locations. Soil sample data was selected from the North American Proficiency Testing program (http://www.naptprogram.org/), which is administered by the Soil Science Society of America (Madison, WI, USA)

		P_2O_5 pounds per 1000 square feet[a]									
Soil sample origin	Phosphorus soil extractant	Pennsylvania State University	Clemson University[b]	University of Florida	University of Wisconsin[c]	University of Wisconsin[d]	Kansas State University	Texas A&M University	North Dakota State University	Utah State University	MLSN
Texas	Bray P1 (1:10)	–[e]	–	–	0[f]	0	0	–	–	–	–
	Mehlich 1	–	0	–	–	–	–	–	–	–	–
	Mehlich 3	1	–	0	0	0	–	0	–	–	0
	Olsen	–	–	–	–	–	–	–	2	0	–
Pennsylvania	Bray P1 (1:10)	–	–	–	2.0	2.0	1	–	–	–	–
	Mehlich 1	–	4.6	–	–	–	–	–	–	–	–
	Mehlich 3	2	–	0.2	0	0	0	0	-	-	0
	Olsen	–	–	–	–	–	–	–	3	1	–
Illinois	Bray P1 (1:10)	–	–	–	2.0	3.5	2	–	–	–	–
	Mehlich 1	–	2.3	–	–	–	–	–	–	–	–
	Mehlich 3	2	–	0.2	0.5	1.0	–	0	–	–	0
	Olsen	–	–	–	–	–	–	–	2	1	–

[a]Soil fertility recommendations for the maintenance of high-quality, cool-season turfgrass.
[b]Creeping bentgrass putting greens.
[c]Sand-based greens.
[d]High-traffic turfgrass areas, push-up tees, and greens (excludes sand greens).
[e]Hyphens indicate that a lab does not use the extractant.
[f]To convert pounds per 1000 square feet to kg per hectare, multiply cell values by 48.8.

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for sand-based putting greens and Kansas State ratings (both Bray P1) for the Illinois soil were ‘Low’ and ‘Medium’, respectively (Table 3), and would each result in recommendations for 2 pounds P_2O_5 per 1000 square feet (98 kg P_2O_5 per hectare) (Table 4). Mehlich 3 ratings were ‘Medium’ (or ‘Below Optimum’) for Penn State, ‘Medium’ for the University of Florida, ‘Medium’, for Texas A&M, and ‘Sufficient’ for the MLSN. Depending on the specific lab, these ratings result in a range of recommendations for P fertilizer from 0 pounds P_2O_5 per 1000 square feet (0 kg P_2O_5 per hectare) (Texas A&M and MSLN) to 2.5 pounds P_2O_5 per 1000 square feet (122 kg P_2O_5 per hectare) (Penn State). Though not appropriate for Illinois, interpretation based on Olsen extraction and calibrations from North Dakota State or Utah State yielded similar fertilizer recommendations in this case. The same is true for the Mehlich 1 extraction and calibration from Clemson. The University of Wisconsin calibrations are likely the closest to conditions from the Illinois sample, so Texas A&M and MLSN Mehlich-3 calibrations may be underestimating the amount of P fertilizer necessary for the Illinois sample.

3.3.2 Potassium

Extractable K levels were less extractant-dependent than extractable P for these samples, but K fertilizer recommendations were more variable than the P recommendations. Beginning with the sample from Texas, ammonium acetate, Mehlich-3, and Olsen extractants could be appropriate and yielded 41 $mg{\cdot}kg^{-1}$, 45 $mg{\cdot}kg^{-1}$, and 41 $mg{\cdot}kg^{-1}$ extractable P, respectively (Table 2). Kansas State and Utah State ratings for ammonium acetate were ‘Low’ (41–175 $mg{\cdot}kg^{-1}$) and ‘Very low’ (<75 $mg{\cdot}kg^{-1}$) for the Texas sample (Table 2), respectively, and recommend 4.0 and 2-3 pounds K_2O per 1000 square feet (195 K_2O kg per hectare and 98–146 K_2O kg per hectare) (Table 4). Mehlich-3-based soil ratings were ‘Medium’ (or ‘Below Optimum’) for Penn State (<180 $mg{\cdot}kg^{-1}$), ‘Medium’ for the University of Florida (36–60 $mg{\cdot}kg^{-1}$), and ‘Low’ for Texas A&M (0–75 $mg{\cdot}kg^{-1}$), yielding recommendations for 0.5 pounds K_2O per 1000 square feet (24 kg K_2O per hectare) (University of Florida) to 5 pounds K_2O per 1000 square feet (244 kg K_2O per hectare) from Penn State. More frugally, the MLSN rates the Texas sample as ‘Sufficient’ (>37 $mg{\cdot}kg^{-1}$) resulting in a recommendation for no K fertilizer. The Olsen rating from North Dakota State was ‘Low’ and yielded a recommendation for 4 pounds K_2O per 1000 square feet (195 kg K_2O per hectare). As the recommendation from Texas A&M was for 2.9 pounds K_2O per 1000 square feet (142 kg K_2O per hectare), recommendations above and below this level likely have over- and underestimated the amount of K fertilizer needed.

The Pennsylvania and Illinois samples had more extractable K than the Texas sample and were quite similar, resulting in identical fertilizer recommendations. The samples (Pennsylvania-Illinois) had 97–113 $mg{\cdot}kg^{-1}$, 99–114 $mg{\cdot}kg^{-1}$, and 83–89 $mg{\cdot}kg^{-1}$ extractable K-based and ammonium acetate, Mehlich 3, and Bray extractants, respectively (Table 2). The ammonium acetate ratings were 'Low' for Kansas State and Utah State calibrations (Table 3), yielding recommendations for 4.0 pounds K_2O per 1000 square feet and 2 pounds K_2O per 1000 square feet, respectively (195 kg K_2O per hectare and 98 kg K_2O per hectare, respectively) (Table 5). The Mehlich 3 ratings were 'Medium' (or 'Below Optimum') for Penn State (<180 $mg{\cdot}kg^{-1}$), 'High' for the University of Florida (>60 $mg{\cdot}kg^{-1}$), and 'Medium' for Texas A&M (75–125 $mg{\cdot}kg^{-1}$), yielding recommendations for 0 pounds K_2O per 1000 square feet (0 kg K_2O per hectare) (University of Florida) to 3 pounds K_2O per 1000 square feet (146 kg K_2O per hectare) from Penn State. Again, the MLSN rating was 'Sufficient.' The University of Wisconsin lab uses Bray P1 for K extraction and rated the Illinois and Pennsylvania soils as 'Low' for golf turf with a recommendation for 3 pounds K_2O per 1000 square feet (146 kg K_2O per hectare), but 'Very High' for general turf (non-golf) with no K_2O recommended, highlighting the potential importance of land use for soil test interpretations and fertilizer recommendations. As discussed for P, the Penn State and University of Wisconsin recommendations likely should be considered the most accurate for samples from Pennsylvania and Illinois, respectively.

3.4 Case study conclusion

This case study reinforces the numerous ways that turfgrass fertilizer recommendations can be inaccurate and result in too little or too much fertilizer use. We only discussed P and K for simplicity, but similar issues exist with soil test interpretation for other nutrients. When submitting soil samples for testing, rating, and recommendations, it is always best to use regionally appropriate extractants and SLANs from local turfgrass calibration data – hopefully with the exact turf species and soil properties as the origin of the sample. Because this calibration data does not exist for all nutrients for all turfgrass species on all soils and in all locations, or – even less inspiring – for all turf cultivars on all soils and in all locations, concessions are inevitable. At a minimum, a turfgrass manager should ask for a regionally appropriate extractant and seek SLANs based on that extractant that have been calibrated to a soil similar to what is at their site. If local SLANs are unavailable, the MLSN is a reasonable guide for tests from Mehlich 3 extractions and will, at worst, underpredict the amount of fertilizer needed. In these cases, inspection for visual deficiency symptoms validated by low rates of the suspected deficient nutrient can help a turf manager adjust MLSN guidelines to their site.

4 Conclusion and future trends

The axiom 'don't guess, soil test' is used to convey the idea that soil testing helps turfgrass managers follow precise guidelines to prevent the over-application

Table 5 Potassium fertilizer recommendations from different laboratories utilizing frequently used soil extractants for soil samples from three locations. Soil sample data was selected from the North American Proficiency Testing program (http://www.naptprogram.org/), which is administered by the Soil Science Society of America (Madison, WI, USA)

		K_2O pounds per 1000 square feet[a]									
Soil sample origin	Potassium soil extractant	Pennsylvania State University	Clemson University[b]	University of Florida	University of Wisconsin[c]	University of Wisconsin[d]	Kansas State University	Texas A&M University	North Dakota State University	Utah State University	MLSN
Texas	Ammonium acetate	–[e]	–	–	–	–	4[f]	–	–	2-3	–
	Mehlich 1	–	4.6	–	–	–	–	–	–	–	–
	Mehlich 3	5	–	0.5	–	–	–	2.9	–	–	0
	Bray P1	–	–	–	4	2	–	–	–	–	–
	Olsen	–	–	–	–	–	–	–	4	–	–
Pennsylvania	Ammonium acetate	–	–	–	–	–	4	–	–	2	–
	Mehlich 1	–	2.3	–	–	–	–	–	–	–	–
	Mehlich 3	3	–	0	–	–	–	0	–	–	0
	Bray P1	–	–	–	3	0	–	–	–	–	–
	Olsen	–	–	–	–	–	–	–	4	–	–
Illinois	Ammonium acetate	–	–	–	–	–	4	–	–	2	–
	Mehlich 1	–	2.3	–	–	–	–	–	–	–	–
	Mehlich 3	3	-	0	–	–	–	0	–	–	0
	Bray P1	-	-	-	3	0	–	–	–	–	–
	Olsen	-	-	-	–	–	–	–	4	–	–

[a]Soil fertility recommendations for the maintenance of high-quality, cool-season turfgrass.
[b]Creeping bentgrass putting greens.
[c]Recommendations specific to golf course turf.
[d]Recommendations specific to general turf areas, excluding golf turf.
[e]Hyphens indicate that a lab does not use the extractant.
[f]To convert pounds per 1000 square feet to kg per hectare, multiply cell values by 48.8.

of fertilizer. A recent survey of golf course superintendents found that the most common nutrient conservation technique was to fertilize based on soil test results, with 55% of respondents using this method (Gelernter et al., 2016). However, the same survey reported that golf course superintendents who used soil testing applied significantly more nutrients than golf courses that did not soil test. While soil testing can prevent over-application of nutrients, the situation where soil test recommendations result in more nutrient use than normally would occur appears to be at least as likely. While the phrase 'guess, don't soil test' will never catch on, the fertilizer recommendations from a soil test are only as good as the correlation, calibration, and interpretation work that was used to create the recommendations. Continued scrutiny of existing recommendations and additional research into soil testing for turfgrass should remain a high priority.

In the absence of good soil-testing data, recommendations tend to be conservative – meaning the recommendations will skew toward applying more nutrients than the turfgrass actually requires. However, over applications of nutrients because of soil testing are not simply because of conservative recommendations alone. Unfortunately, some recommendations are more spurious. While most soil-testing laboratories report the soil test values and compare against some research-based guidelines (which may or may not result in a fertilizer recommendation), sometimes a secondary party (often a consulting agronomist or fertilizer company) will send client's soil samples to a reputable laboratory but disregard the laboratory's recommendations and instead use their own interpretation and recommendations from the laboratory results. The quality of these recommendations varies. In some cases, the recommendations are drastically different from research-based results. For example, SPE (which is useful for pH and salt and sodium hazard evaluation) is inappropriately but commonly used to make nutrient recommendations. SPEs are unable to extract the nutrients on the cation exchange sites and are also unable to extract much P because of that nutrient's low solubility in soil solution. Therefore, the nutrient levels in the saturated paste are much lower than the levels extracted by conventional soil nutrient extractants, and the fertilizer or consulting agronomist may recommend applying nutrients with a justification that says that while the conventional soil test finds adequate nutrition, the nutrients are actually 'locked up' in the soil and the saturated paste test correctly shows that nutrients are low.

The most common justification for using SPE to make fertilizer recommendations is that by mixing water with soil, the saturated paste test is mimicking what the plant actually 'sees.' This sounds logical to a layperson but ignores fundamental knowledge about soil science and plant nutrition. Laboratories and secondary parties that follow scientific principles do not use this method for nutrient recommendations. Turfgrass managers using this method are wasting time, money, and likely contributing to non-point source pollution. Interpretations from secondary parties are not always negative, however. In fact, a secondary party can improve on a laboratory's recommendation by using local knowledge and incorporating the latest scientific results that laboratories may be slower to adopt. It is up to the end user to determine if the secondary party is reliable or not and use of the saturated paste test to make nutrient recommendations is an easy way to identify an unreliable interpretation.

In summary, soil testing can be a valuable method to help turfgrass managers make fertilizer decisions. There are many different methods for soil testing and choosing the most appropriate soil test extractant is key. Whether an extractant is appropriate depends on the physical and chemical properties of the soil or rootzone in question and the availability of data that correlates extracted nutrient concentrations to the performance of the managed turfgrass species in the desired region. Recommendations from this scenario are ideal and allow turf managers to judiciously apply fertilizer. However, while the database of soil test interpretations is growing, there are many gaps to be filled by soil test calibration research. There also are nutrients (e.g. N, S, and most micronutrients) for which we do not have much or, in some cases, any reliable soil test calibration data. Because of the innumerable soil nutrient calibration scenarios among soil types, geographies, and turfgrass species (or even varieties), it is likely that the perfect soil-testing database will never exist. This reality has advanced creative research and interpretation to define sufficiency levels for some nutrients in broad terms (e.g. the MLSN). These guidelines are straightforward and partially fill the void of needed soil test calibration research, which has normalized their use in recent years. Conversely, and without question, turfgrass managers should be skeptical of fertilizer recommendations based on an inappropriate extractant, calibration, or, especially, one based on SPE or ideal ratios or of major exchangeable cations (i.e. BCSR).

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