between shoots and roots of Kentucky bluegrass. Crop Sci. 39: 746–754.


ABSTRACT

Methods for determining K deficiencies in alfalfa (Medicago sativa L.) are either imprecise, time-consuming, or expensive. New to the market are portable and inexpensive meters that use a K-specific electrode (KSE) to measure the K concentration of plant sap. Little research has examined the precision or accuracy of these meters for determining the K concentration in alfalfa shoots. The objective was to determine if the KSE meter could precisely and accurately estimate the K concentration in alfalfa shoots. Laboratory, greenhouse, and field experiments were conducted to test the KSE meter’s ability to measure the concentration of K in aqueous solution and in alfalfa sap. Laboratory results showed that KSE meter readings are subject to interference from Cl−, SO42− and NO3− ions. In greenhouse and field experiments, the KSE meter precisely estimated the K concentration in alfalfa shoots (R2 > 0.74) if readings were included in a multiple regression equation that also included sample moisture content or mean stage count and air temperature. Readings taken from fresh plant sap using the KSE meter were highly biased, with the readings being four to six times lower than those obtained by flame photometry. Readings from the KSE meter, if used with other variables in a multiple regression equation, would allow users to quickly assess the K status of alfalfa shoots for a relatively small investment.

WELL-NODULATED ALFALFA removes more K from the soil than any other nutrient. Alfalfa requires K to catalyze several metabolic functions. Functions such as enzyme activation, transpiration, translocation of photoassimilates, protein and starch synthesis, and energy relations all depend on K (Lanyon and Smith, 1985; Tisdale et al., 1985; Li et al., 1997). Consequently, a K deficiency in alfalfa reduces forage yield and stand life (Sheaffer et al., 1986; Kitchin et al., 1990; Li et al., 1997).

Many soils in the central USA do not contain adequate supplies of K for satisfactory alfalfa growth without application of fertilizer (Fixen, 1998). Potassium deficiencies occur most frequently in unfertilized or naturally infertile soils where alfalfa and other forage crops are often planted (Follett and Wilkinson, 1985). Potassium deficiencies in these soils cost alfalfa producers in the central USA an estimated $500 million annually (Fixen, 1998; Miller and Reetz, 1995). Rapid detection and correction of K deficiencies would allow producers to minimize these losses.

Visual symptoms of K deficiency are difficult to see before reductions in yield or stand life occur. One of the best ways to assess the K status of alfalfa is by tissue testing. Tissue testing provides an accurate estimate of the K concentration in alfalfa and is often more sensitive than soil testing. Tissue testing often indicates a problem with K nutrition before soil testing, allowing producers to correct K fertility problems before alfalfa yields decline (Mills and Jones, 1996). The recommended method for sampling alfalfa is to remove the upper 15 to 20 cm from 25 to 50 shoots in each field and then have the samples analyzed by a certified laboratory (Mills and Jones, 1996). Most laboratories analyze samples for K concentration using either flame photometry or inductively coupled plasma–optical emission spectroscopy.

Abbreviations: KSE, K-specific electrode; MSC, mean stage count; SEP, standard error of prediction.
For producers, this process is costly ($10–20 per sample) and time consuming. Consequently, the number of samples producers are willing to take is limited. Methods that lower the cost and time required for assessing the K status of alfalfa would improve fertilizer efficiency by promoting frequent and site-specific monitoring.

Small, portable meters that have a K-specific electrode (KSE meter) have recently been developed for determination of K in plant sap. These meters are inexpensive (about $350), simple to operate, and designed for field use. Preliminary results in the western USA showed that readings from the KSE meter were correlated ($r^2 = 0.68$) with the K concentration in alfalfa shoots (Kallenbach, 1997), but further research was needed to improve the precision of this technology. Research on a variety of crops shows that KSE meter readings are influenced by tissue anion concentration (mainly $\text{Cl}^-$ and $\text{NO}_3^-$), plant growth stage, and air temperature (Morse et al., 1992; Hodges and Baker, 1993; Kallenbach, 1997). The impact of these influences needs to be quantified for alfalfa to determine ways of minimizing interferences and improving the precision of K monitoring in the field.

The overall objective of this study was to determine if the KSE meter could accurately and precisely estimate the K concentration in alfalfa shoots. Specific objectives were (i) to determine if the anions $\text{Cl}^-$, $\text{SO}_4^{2-}$, and $\text{NO}_3^-$ influence KSE meter readings, (ii) to determine if KSE meter readings taken from plant sap could precisely and accurately estimate the K concentration in alfalfa shoots, and (iii) to evaluate other parameters easily measured in the field that could be used in multiple regression to improve the precision and accuracy of the KSE meter.

**MATERIALS AND METHODS**

**Laboratory Experiment**

The ability of the KSE meter (Horiba Corp., Kyoto, Japan) (Fig. 1) to measure K concentration in the presence of $\text{Cl}^-$, $\text{SO}_4^{2-}$, and $\text{NO}_3^-$ ions was determined by preparing aqueous solutions of KNO$_3$, KCl, and K$_2$SO$_4$ at concentrations of 0, 0.010, 0.100, 1.0, 2.0, 4.0, 6.0, 8.0, and 10 g L$^{-1}$ of K. Solutions were tested by placing a sampling paper over the electrode and testing the KSE meter (Table 1). Each treatment was replicated four times (3 pots $\times$ 4 treatments). Regression coefficients comparing KSE meter readings with results from the Kspecific electrode (Kallenbach, 1998, unpublished data). The treatment was replicated four times (3 pots = 1 replication) in a randomized complete block design.

Shoots were harvested to a 5-cm stubble height 84 d after planting, the length of the longest stem and mean stage count (MSC) was recorded for every sample (Kalu and Fick, 1981). The upper 15 to 20 cm of shoots were then clipped and retained for analysis; the lower portion of shoots was discarded. The upper portion of the shoot was cut into 1-cm-long pieces and mixed by hand. Plant sap was extracted with a garlic press (Zyliss Corp., Lyss, Switzerland) and the sap was analyzed with the KSE meter. The other half of the sample was weighed wet, dried for 96 h at 55°C in a forced-air oven, reweighed, and the moisture content calculated. The dried tissue was retained for determination of K by flame photometry (Johnson and Ulrich, 1959).

To ensure precise readings, the KSE meter was washed with distilled water between samples and a two-point calibration performed twice daily. Duplicate readings were taken with
Table 1. Maximum, minimum, mean, and standard deviation of variables used in regression analysis to test the precision and accuracy of the K-specific electrode (KSE) meter to measure the K concentration in alfalfa shoots.²

<table>
<thead>
<tr>
<th></th>
<th>K concentration³</th>
<th>KSE meter readings</th>
<th>Moisture content</th>
<th>Mean stage count</th>
<th>Length of longest stem</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greenhouse experiment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>29.8</td>
<td>7.45</td>
<td>808</td>
<td>2.57</td>
<td>66</td>
<td>38</td>
</tr>
<tr>
<td>Minimum</td>
<td>7.8</td>
<td>1.60</td>
<td>695</td>
<td>0.46</td>
<td>31</td>
<td>24</td>
</tr>
<tr>
<td>Mean</td>
<td>21.8</td>
<td>4.36</td>
<td>760</td>
<td>1.31</td>
<td>47</td>
<td>30</td>
</tr>
<tr>
<td>SD</td>
<td>5.3</td>
<td>1.40</td>
<td>29</td>
<td>0.50</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td><strong>Field experiment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>44.6</td>
<td>7.20</td>
<td>851</td>
<td>6.58</td>
<td>109</td>
<td>35</td>
</tr>
<tr>
<td>Minimum</td>
<td>15.0</td>
<td>2.25</td>
<td>713</td>
<td>0.22</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>Mean</td>
<td>25.7</td>
<td>5.01</td>
<td>775</td>
<td>2.54</td>
<td>66</td>
<td>28</td>
</tr>
<tr>
<td>SD</td>
<td>6.9</td>
<td>1.32</td>
<td>35</td>
<td>1.35</td>
<td>25</td>
<td>3</td>
</tr>
</tbody>
</table>

² Data for the greenhouse experiment represent 72 samples collected from plants treated with six levels of K in the greenhouse. Data for the field experiment represent samples collected from commercial alfalfa fields in 30 locations.

³ Potassium concentration measured from dry samples using flame photometry.

The KSE meter was tested at 30 different locations to determine its suitability under field conditions. Commercial alfalfa fields were sampled beginning in May and ending in August of 1998. Fields represented a wide range of soil types, cultivars, growth stages, K nutrition, and other conditions. At each field, 50 to 60 randomly chosen stems were cut to a 5-cm stubble height and processed in the same manner as described for the greenhouse experiment. The same parameters that were measured in the greenhouse experiment (moisture content, MSC, length of the longest stem, and air temperature) were recorded and used in multiple regression (Neter et al., 1989) to ascertain their influence on KSE meter readings.

Field Experiment

The KSE meter was tested at 30 different locations to determine its suitability under field conditions. Commercial alfalfa fields were sampled beginning in May and ending in August of 1998. Fields represented a wide range of soil types, cultivars, growth stages, K nutrition, and other conditions. At each field, 50 to 60 randomly chosen stems were cut to a 5-cm stubble height and processed in the same manner as described for the greenhouse experiment. The same parameters that were measured in the greenhouse experiment (moisture content, MSC, length of the longest stem, and air temperature) were recorded and used in multiple regression (Neter et al., 1989).

RESULTS AND DISCUSSION

Laboratory Experiment

Readings from the KSE meter increased linearly as the K concentration of each solution increased (Fig. 2). The meter readings were highly correlated ($R^2 = 0.96–0.99$) with the K concentrations, but the KSE meter gave a different regression equation for KCl than for KNO$_3$ or K$_2$SO$_4$ ($P \leq 0.05$). Solutions of KCl had a slope of 0.81, which was 27 to 30% greater than the slope for solutions of KNO$_3$ or K$_2$SO$_4$. Thus, while the precision of the KSE meter was high, the meter gave readings that were more accurate (slope closer to 1) for KCl than for KNO$_3$ or K$_2$SO$_4$. These results suggest that the KSE meter works, at least in part, on electrical conductivity. Since KCl has a higher electrical conductivity than either KNO$_3$ or K$_2$SO$_4$ (Dobos, 1975), it is not surprising that solutions of KCl gave higher readings than did solutions of KNO$_3$ or K$_2$SO$_4$.

These findings suggest that KSE meter readings depend not only on the K concentration in plant sap, but also on which other minerals or compounds are present. If plants contained high levels of Cl$^-$, the KSE meter readings might be higher than if plants contained high levels of SO$_4^{2-}$ or NO$_3^-$.$^2$. This would lead to errors when testing diverse species that accumulate differing ratios of these ions. Several researchers reported that the K to Cl and K to S ratios vary widely among species (National Research Council, 1982; Collins, 1989). In addition, McKimnie and Dobrenz, (1991) found that salt-tolerant genotypes of alfalfa had a higher K/Cl ratio than non-salt tolerant genotypes. Using the KSE meter to compare the K concentrations of many different species or diverse cultivars of a single species may lead to erroneous or biased results. Further testing under these conditions is warranted.

Greenhouse Experiment

In the greenhouse experiment, the K concentration of alfalfa samples ranged from 7.8 to 29.8 g kg$^{-1}$ (Table 1). Mills and Jones (1996) reported that the upper 15 cm of alfalfa shoots require a minimum of 20 g kg$^{-1}$ of K in dry tissue for optimum growth. Using this as a guideline, 22 of the 72 samples tested with the KSE meter would be considered K deficient.

When regressed alone, KSE meter readings increased by 2.9 g kg$^{-1}$ for every 1 g kg$^{-1}$ increase in the K concentration of dry tissue as determined by flame photometry (Table 2). The KSE meter alone explained 60% of the variation in K concentration and had a standard error of prediction (SEP) that was <10% of the mean. Adding other parameters (moisture content, MSC, length of the longest stem, and air temperature) in multiple regression...
sion significantly \((P \leq 0.05)\) improved the model \(R^2\)'s, with moisture content making the greatest single improvement \((R^2 = 0.76)\) (Table 2). More complex regression models that included three or more variables gave only slightly higher \(R^2\)'s than the two-variable model of KSE meter reading and moisture content. The three-variable model with the highest \(R^2\) (0.79) included the KSE meter reading, moisture content, and the length of the longest stem. Regression models that included four or more variables did not show any improvement in \(R^2\) compared with the best three-variable model.

While the KSE meter readings plus moisture content was the best two-variable model, determining the moisture content of samples is sometimes impractical or time consuming. Use of a microwave oven could make this fairly rapid, but would require extra equipment and time (Steevens et al., 1986). If moisture content could not be obtained, then using a three-variable model that included air temperature and either length of the longest stem or MSC would be faster and give results almost as precise \((R^2 = 0.74)\).

Although results from the greenhouse show that the KSE meter can be precise if other parameters are measured, there was a large bias between absolute readings.

Table 2. Regression models for predicting the K concentration in alfalfa shoots with the K-specific electrode (KSE) meter when grown under six levels of K fertility in the greenhouse. Models include using the KSE meter only and using the KSE meter with moisture content, mean stage count, length of the longest stem, and temperature as variables in multiple regression.†

<table>
<thead>
<tr>
<th>Model</th>
<th>Regression equation†</th>
<th>(R^2)</th>
<th>SEP§</th>
</tr>
</thead>
<tbody>
<tr>
<td>KSE meter</td>
<td>(y = 8.9^* + 2.9K^*)</td>
<td>0.60</td>
<td>0.43</td>
</tr>
<tr>
<td>KSE meter + moisture</td>
<td>(y = 60.1^* + 3.8K^* + 0.09M^*)</td>
<td>0.76</td>
<td>0.34</td>
</tr>
<tr>
<td>KSE meter + mean stage count</td>
<td>(y = 11.6^* + 3.3K^* - 3.4MSC^*)</td>
<td>0.69</td>
<td>0.38</td>
</tr>
<tr>
<td>KSE meter + length of longest stem</td>
<td>(y = 15.0^* + 3.2K^* - 0.16L)</td>
<td>0.66</td>
<td>0.40</td>
</tr>
<tr>
<td>KSE meter + temperature</td>
<td>(y = 22.1^* + 3.5K^* - 0.53T^*)</td>
<td>0.71</td>
<td>0.36</td>
</tr>
<tr>
<td>KSE meter + moisture + mean stage count</td>
<td>(y = 46.9^* + 3.8K^* + 0.07M^* - 1.5MSC)</td>
<td>0.77</td>
<td>0.33</td>
</tr>
<tr>
<td>KSE meter + moisture + length of longest stem</td>
<td>(y = 50.4^* + 4.0K^* + 0.08M^* - 0.13L^*)</td>
<td>0.79</td>
<td>0.31</td>
</tr>
<tr>
<td>KSE meter + moisture + temperature</td>
<td>(y = 45.0^* + 3.8K^* + 0.07M^* - 0.13T)</td>
<td>0.76</td>
<td>0.34</td>
</tr>
<tr>
<td>KSE meter + mean stage count + length of longest stem</td>
<td>(y = 14.0^* + 3.4K^* - 2.7MSC^* - 0.08L)</td>
<td>0.70</td>
<td>0.37</td>
</tr>
<tr>
<td>KSE meter + mean stage count + temperature</td>
<td>(y = 20.3^* + 3.6K^* - 2.0MSC^* - 0.39T^*)</td>
<td>0.74</td>
<td>0.35</td>
</tr>
<tr>
<td>KSE meter + length of longest stem + temperature</td>
<td>(y = 24.6^* + 3.6K^* - 0.11L^* - 0.46T^*)</td>
<td>0.74</td>
<td>0.35</td>
</tr>
<tr>
<td>KSE meter + moisture + mean stage count +</td>
<td>(y = 49.0^* + 4.0K^* + 0.08M^* + 0.21MSC - 0.12L^*)</td>
<td>0.79</td>
<td>0.31</td>
</tr>
<tr>
<td>length of longest stem</td>
<td>(y = 37.8^* + 3.8K^* + 0.06M^* - 1.4MSC - 0.09T)</td>
<td>0.77</td>
<td>0.33</td>
</tr>
<tr>
<td>KSE meter + moisture + mean stage count + length of longest stem + temperature</td>
<td>(y = 48.0^* + 4.0K^* + 0.08M^* - 0.12L^* - 0.02T)</td>
<td>0.79</td>
<td>0.31</td>
</tr>
<tr>
<td>KSE meter + mean stage count + length of longest stem + temperature</td>
<td>(y = 22.7^* + 3.6K^* - 1.3MSC - 0.08L - 0.39T^*)</td>
<td>0.75</td>
<td>0.35</td>
</tr>
<tr>
<td>KSE meter + moisture + mean stage count +</td>
<td>(y = 46.9^* + 4.0K^* + 0.08M^* - 0.20MSC - 0.12L^* - 0.02T)</td>
<td>0.79</td>
<td>0.32</td>
</tr>
</tbody>
</table>

* = coefficient significant \(P \leq 0.05\).
† Data are pooled across three harvests and four replications.
‡ \(y\) = potassium content of dry alfalfa tissue \((\text{g kg}^{-1})\); K = KSE meter readings from fresh plant sap \((\text{g kg}^{-1})\); M = moisture content of sample \((\text{g kg}^{-1})\); L = length of longest stem \((\text{cm})\); T = temperature \((\text{°C})\); MSC = mean stage count.
§ SEP = standard error of prediction.
from the KSE meter and those obtained from flame photometry. The readings from the KSE meter were four to five times lower than values from flame photometry (Table 1). Left uncorrected, this lack of accuracy could lead to an incorrect evaluation of the K status of alfalfa.

**Field Experiment**

Readings from the KSE meter, when regressed alone, accounted for only 37% of the variation in K concentration from alfalfa collected from commercial fields (Table 3). The $R^2$ was lower than that found in the greenhouse experiment probably because of the more diverse environmental conditions in the field. The alfalfa stands sampled differed widely in stage of maturity, moisture content, and K concentration (Table 1) as well as other variables such as cultivar, soil type, and soil fertility. These variables no doubt contributed to the low $R^2$ for the KSE meter when regressed alone.

Adding any single variable to the model, except for air temperature, significantly improved the prediction of the K concentration in alfalfa. As was found in the greenhouse experiment, moisture content was the single best variable to add, improving the $R^2$ to 0.85 (Table 3). Mean stage count was the second best single variable ($R^2 = 0.73$), followed by length of the longest stem ($R^2 = 0.67$). Models that included three or more variables showed only small, if any, improvement in $R^2$ compared with the two-variable model of KSE meter reading and moisture content. Three-variable models that included moisture content consistently had the highest $R^2$s and the lowest SEPs (Table 3). The three-variable model with the highest $R^2$ (0.89) included the KSE meter reading, moisture content, and length of the longest stem. This model also gave the highest $R^2$ in the greenhouse experiment, which indicates that this model would be most precise.

Two, three-variable models that gave acceptable $R^2$s but that did not include moisture content were found. The three-variable models that included the KSE meter reading with MSC and the length of the longest stem or MSC and air temperature produced $R^2$s of 0.78 and 0.77, respectively. These two models might be more practical for field use. We preferred the model that included the KSE meter reading, MSC, and air temperature because it took only 30 min to obtain the data for a single reading yet still had a high $R^2$ in both the greenhouse and field.

Although many of the models indicate that the KSE meter, when used in conjunction with other parameters, can be precise, most of the absolute readings from the field had a large bias. As was found in the greenhouse experiment, readings from the KSE meter taken from fresh plant sap were approximately four to six times lower than the K concentration in dry tissue analyzed by flame photometry. Users unaware of this relationship could mistakenly underestimate the K concentration of alfalfa tissue if readings from the KSE meter were used directly. Producers and crop consultants could overcome this problem by using the appropriate regression equation reported in Table 3.

There was a surprisingly small difference in the slope coefficients found for the same model whether in the greenhouse or in the field (Tables 2 and 3). When comparing like models, in all but a few cases, the slope coefficients obtained for greenhouse samples were within 35% of those obtained from the field samples. This suggests that readings from the KSE meter might be more stable under a variety of conditions than results from the laboratory experiment first indicated.

**CONCLUSIONS**

Results from the laboratory experiment suggest that the KSE meter is subject to interference from Cl−,
SO$_4^{2-}$, and NO$_3^-$ when assaying solutions. However, results from greenhouse and field experiments suggest that this may not be a problem when testing alfalfa shoots. The KSE meter precisely estimated the K concentration in alfalfa shoots if other variables, especially moisture content, were included in multiple regression. If users could not obtain moisture content, then using MSC and air temperature along with the KSE meter reading in multiple regression would be almost as precise.

Readings from KSE meter, when combined with other variables, give producers and crop consultants the ability to quickly assess the K status of alfalfa for a relatively small investment. Producers and crop consultants should realize that the absolute values from the KSE meter are much lower than those obtained from flame photometry. In addition to obtaining a reading from the KSE meter, field users will need to measure either sample moisture content or MSC and air temperature and then convert readings with the appropriate multiple regression equation listed in Table 3. Converted readings could then be used to make K fertilizer decisions based on the current guidelines developed for flame photometry.

REFERENCES


