Testing the Assumption of Normality for pH and Electrical Conductivity of Substrate Extract Obtained Using the Pour-through Method

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Abstract. The pour-through method is a simple and useful technique for on-site monitoring of pH and electrical conductivity (EC) in container nurseries, and has also been used in numerous research studies focused on substrates, plant nutrition, and plant production. Linear models, including the special cases of analysis of variance and linear regression analysis, are often used for statistical analysis of extract data and are readily available as procedures in statistical software packages. Certain assumptions, including normality of the data values or model residuals, are required to develop valid statistical inferences using linear models. This study evaluated the normality of pH and EC variables using data obtained from 100 extract samples collected weekly over 12 weeks using the pour-through method from a uniform containerized substrate (25 pine bark : 18 peatmoss : 7 sand blend amended with calcium sulfate and top-dressed with Polyon 17N–2.1P–9.1K + micros, a 365-day controlled-release fertilizer, at 10 g/container) in 2.8-L containers. Graphical techniques (histograms and QQ plots) and formal goodness-of-fit tests (tests based on the empirical distribution function, moment tests, and the Shapiro-Wilk regression test) were used to demonstrate methods for assessing normality. The variables pH and EC both exhibited relatively normal distributions. For comparative purposes, the transformed variables $\ln(\text{pH})$, $10^{-\text{pH}}$, and $\ln(\text{EC})$ were also evaluated. The latter two variables exhibited significant departures from normality, whereas $\ln(\text{pH})$ did not. Average weekly EC exhibited positive correlations with time-lagged, average weekly substrate temperature, suggesting that nutrient release from the controlled-release fertilizer could be more dependent on temperature in the second to fourth weeks preceding extraction than on temperature in the week immediately preceding extraction.

The pour-through method was developed as a simple and rapid means of monitoring pH, soluble salts [electrical conductivity (EC)], and nutrient availability in the soil solution of containerized substrate (Wright, 1984, 1986). Solutions for analysis are obtained by pouring a predetermined volume of distilled water onto the surface of the substrate to displace the soil solution and collecting the liquid that drains from the bottom of the container. The method has been recommended for on-site analysis of pH and EC as a regular practice in container nursery production programs (Bilderback, 2001; Cavins et al., 2000; Garber and Ruter, 1993; Ruter and Garber, 1993).

Studies have demonstrated the usefulness of the pour-through method in monitoring the chemical properties of container substrate in comparison with other extraction methods

(Hipp et al., 1979; Wright et al., 1990; Yeager et al., 1983). Equations have been published for converting values from one extraction method to another (Cavins et al., 2004; Huang et al., 2000, 2001; McLachlan et al., 2004). Greater variability in readings between extraction methods may occur with pH depending on type of substrate, EC, and other factors (Cabrera, 1998; Handreck, 1994).

Numerous substrate, plant nutrition, and plant production studies have used the pour-through method to examine pH, EC, and nutrients in the soil solution of container substrates (Blythe et al., 2002; Chen et al., 2003; Cole et al., 2005; James and van Iersel, 2001; Kang and van Iersel, 2002; Karam et al., 1994; Niemiera and Leda, 1994; Niemiera et al., 1994; Rippey and Nelson, 2005; Ruter, 1992; Scoggins, 2005; Tyler et al., 1993; Wright et al., 1999a, b). Most of these studies have involved the use of linear models or special cases of linear models, such as analysis of variance (ANOVA) or linear regression analysis, for statistical analysis of sample data.

Linear models, including ANOVA and linear regression models, are applicable for statistical analysis of data from a wide range

of experimental studies (Littell et al., 2002). However, appropriate use of linear models for statistical inference involves certain assumptions about the data, including normality, constant variance, and independence of the errors (residuals) (Neter et al., 1996). When these assumptions are reasonably satisfied, inferences can be drawn with respect to populations based on the sample data using common statistical techniques including *t* tests, *F* tests, tests on regression parameters, and calculation of confidence intervals and prediction intervals (D'Agostino and Stephens, 1986; Neter et al., 1996). Although some departure from normality does not tend to create a serious problem, the possibility of a serious departure from the assumption of normality should be examined to avoid making invalid inferences from the data (Neter et al., 1996).

Researchers sometimes proceed directly to the use of linear models, ANOVA, or linear regression procedures with statistical analysis software without making an assessment or having prior knowledge of whether the assumption of normality, or at least near-normality, is valid. Such knowledge is not only of value to the researcher in selecting appropriate statistical methods and models, but may also be of value to other researchers working in the same subject area (Shojo and Iwaisaki, 1999; Tang et al., 1999). In the case of linear regression analysis, researchers may limit their analysis to calculating least-squares estimates of linear regression equations, which do not require an assumption about the distribution of the error terms; however, such an assumption is needed to calculate confidence intervals for the regression parameters or to develop confidence bands for the regression lines (Neter et al., 1996).

When a significant departure from normality is identified, the linear model may need to be modified or, in other cases, remedial measures, such as transformation of the response variable (generally investigated when both the normality and constant variance assumptions are violated), may be used to satisfy assumptions (Neter et al., 1996). Generalized linear models may be used in cases when the response variable can be assumed to follow certain other statistical distributions, such as the binomial, negative binomial, Poisson, or exponential distribution (Littell et al., 2002). When assumptions cannot be made about the underlying distribution of the data, nonparametric methods can be used (Hollander and Wolfe, 1999).

A wide variety of goodness-of-fit tests are available to assess the normality of sample data from a single population or, in the cases of linear regression analysis and analysis of variance, from a set of residuals (D'Agostino, 1986b). Because the mean and variance of the population from which the sample is drawn are usually unknown, they are typically estimated by the sample mean and sample variance. Goodness-of-fit tests examine the probability of the null hypothesis (H_0 ;

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the sample values or residuals are drawn from a normal population) being true given the sample data. If the probability is determined to be small, the null hypothesis is rejected and the alternative hypothesis ($H_1: H_0$ is not true) is accepted. Despite the many tests that have been developed for assessing normality or departures from normality, there is no single test that is optimal for all possible deviations from normality.

Graphical techniques, which represent some of the simplest goodness-of-fit tests, can help to identify major departures from the assumed statistical distribution, as well as to reveal interesting features of the data (D'Agostino, 1986a). However, graphical techniques should not be used alone to assess normality, because they may lead to spurious conclusions. Rather, these tools should be used in conjunction with formal hypothesis tests.

Histograms, box plots, and stem-and-leaf plots may be used to assess normality of data values or residuals, provided the sample size is reasonably large (Neter et al., 1996). QQ plots (quantile-quantile plots) use the ordered data values or residuals, plotting the i th ordered value against the expected quantiles. Normality, or near-normality, is suggested by the plotted points falling on, or close to, a line with intercept and slope equal to the sample mean and SD respectively (SAS Institute Inc., 2004).

Formal hypothesis tests for normality can generally be classified into five groups: chi-square tests, empirical distribution function tests, moment tests, regression tests, and other miscellaneous tests (D'Agostino, 1986b).

Chi-square tests involve "discretizing" the observed data values into m cells, counting the number of values in each cell, and comparing these counts (using a chi-square or likelihood ratio statistic) with the expected number for each cell, the latter computed assuming the data values to be normally distributed (D'Agostino, 1986b). Chi-square tests can be of use when the full sample is not available (truncated or censored data) or the data have been grouped into classes, but are not recommended when the full, ungrouped sample data are available (D'Agostino, 1986b; Moore, 1986).

Tests based on the empirical (sample) distribution involve measuring the vertical differences between the empirical distribution function (EDF) of the sample data and the normal cumulative distribution function. Empirical distribution function test statistics include the Kolmogorov-Smirnov statistic (D), the Cramér-von Mises statistic (W^2), and the Anderson-Darling statistic (A^2) (SAS Institute Inc., 2004; Stephens, 1986a). D is a member of the supremum class of EDF statistics and is calculated using the largest vertical distance between the two distributions. W^2 and A^2 belong to the quadratic class of EDF statistics and are calculated using a formula that includes $\Psi(x)$, a function that weights the squared differences between the two distributions. The statistic is W^2 when $\Psi(x) = 1$ and A^2 when $\Psi(x)$ is a specific function of the EDF.

Tests based on moments involve measures of skewness and kurtosis, the third and fourth centralized moments of a distribution (Bowman and Shenton, 1986). Skewness refers to the symmetry of a distribution and kurtosis refers to the peakedness or flatness of a distribution (Larsen and Marx, 2001). The $Z(\sqrt{b_1})$ statistic (D'Agostino, 1970; 1986b) can be used to test H_0 : normality versus H_1 : nonnormality resulting from skewness, whereas the $Z(b_2)$ statistic (Anscombe and Glynn, 1983; D'Agostino, 1986b) can be used to test H_0 : normality versus H_1 : nonnormality resulting from kurtosis. K^2 , the D'Agostino-Pearson chi-square statistic (D'Agostino, 1986b; D'Agostino and Pearson, 1973), uses both $Z(\sqrt{b_1})$ and $Z(b_2)$ to perform an omnibus test of H_0 : normality versus H_1 : nonnormality resulting from skewness or kurtosis.

Regression tests involve plotting X_i , the ordered data values (order statistics), on the x-axis and $F(i)$, a function of i , on the y-axis, fitting a straight line to the points, and calculating a statistic based on this line (Stephens, 1986b). Among the regression tests, perhaps the best known is the Shapiro-Wilk statistic (W). W is a ratio of variances, one variance being the least-squares estimate of the slope of the straight line, and the other being the sample variance (Shapiro and Wilk, 1965).

There are certain difficulties involved in assessing normality using sample data (Neter et al., 1996). First, random variation in a sample can make determination of a probability distribution difficult unless the sample size is large. Second, in the case of regression analysis, the errors (residuals) may not appear to be normally distributed if an inappropriate regression function is used or if the variance of the errors is not constant.

The objectives of the present study were 1) to test the normality of extract pH and EC data obtained using the pour-through method from a container substrate (without plants) using large samples, 2) to test the normality of selected transformations of the pH and EC variables for comparative purposes, 3) to illustrate the use of some graphical and statistical tools for assessing normality, and 4) to examine possible correlations among substrate temperature and extract pH and EC over the 12-week study period. Large samples were collected from containers of a single, uniformly blended and irrigated substrate without plants to preclude the difficulties noted earlier, with repeat samples collected over time to allow a more thorough assessment.

Materials and Methods

Substrate. The substrate used in the study was a 25 pine bark (6.4–9.5 mm) : 18 peatmoss : 7 washed plaster sand (by volume) blend, amended with 0.59 kg·m⁻³ ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.). Bulk density of the sub-

strate was 0.43 g·cm⁻³. On 10 June 2005, 100 no. 1 containers (black, injection molded, polyethylene, side drain holes; 2.8 L, 17.8 cm tall, 15.2 cm top i.d., 13.0 cm bottom i.d.; ProCal Pro Can, South Gate, Calif.) were each filled with 1700 g moist substrate (39% moisture content by weight). Containers were tamped to settle the substrate and create a 2-cm space between the substrate surface and the top of the container. Containers of substrate were spaced on 39 × 19-cm centers on 1.25-cm wire mesh-covered, 84-cm-high wooden benches in a shaded glass greenhouse. The greenhouse was cooled with an evaporative pad and fan cooling system and had no supplementary heat. Sensors were buried in the center of eight randomly selected containers of substrate to record substrate temperature every 15 min during the experimental period using Hobo external data loggers (Onset Computer Corp., Bourne, Mass.). Each container of substrate was evenly top-dressed by hand with 10 g Polyon 17N-2.1P-9.1K + micros (Pursell Technologies, Sylacauga, Ala.), a 365-d controlled-release fertilizer (CRF). The CRF was worked into the upper 0.5 cm of the substrate. Each container of substrate was then irrigated with 1 L deionized water (four applications of 250 mL spaced 30 min apart and applied evenly by hand over the surface of the substrate with a 250-mL graduated cylinder) to saturate the substrate thoroughly, and was allowed to drain freely. During the subsequent 12 weeks of the study, containers of substrate were irrigated in the same manner twice per week (Tuesday and Friday) with 500 mL (2 × 250 mL at each irrigation) of deionized water and allowed to drain freely.

Sampling procedure. Extracts were collected using the pour-through method every Friday beginning 1 h after completion of the Friday irrigation. Extracts were collected beginning 1 week after installation of the study and then weekly for 12 consecutive weeks. Each container of substrate was placed atop a Schedule 40 polyvinyl chloride ring (4.5 cm tall, 10.1 cm i.d., 11.5 mm o.d.) inside a polyethylene bucket (2.4 L, 16.3 cm tall, 15.2 cm top i.d., 12.7 cm bottom i.d.). 100 mL deionized water was poured evenly over the surface of the substrate in each container by hand using a 100-mL graduated cylinder, and extract was allowed to drain into the bottom of the bucket for 30 min. Extract samples (≈90 mL each) were transferred into individual 100-mL polypropylene sample vials. After being emptied, collection buckets were immediately washed, rinsed, and dried. Extract samples were allowed to sit for 2 h in a laboratory to reach room temperature (23 °C) before measuring pH and EC. Extract pH was measured using an HI991301 portable pH/EC/TDS/temperature meter with an HI1288 pH/EC/TDS/temperature probe (Hanna Instruments, Woonsocket, R.I.) to an accuracy of 0.01 pH units. Extract EC was measured using an Accumet AR50 dual-channel pH/ion/conductivity meter with an Accumet 13-620-161 conductivity

electrode (Accumet Engineering Corp., Hudson, Mass.) to an accuracy of 0.0001 dS·m⁻¹.

Graphical and statistical analysis. The variables pH and EC from the weekly extract samples were evaluated for normality using graphical and statistical methods. For comparative purposes, transformed variables were also evaluated: 10^{-pH}, representing an approximation of the hydrogen ion concentration (or hydrogen ion activity), and ln(pH) and ln(EC), representing a common transformation useful in some cases for dealing with nonnormality and nonconstant error variance.

Histograms and comparative normal curves for initial evaluation of the data for each week and each variable were prepared using the HISTOGRAM statement with the NORMAL option under the UNIVARIATE procedure of SAS (version 9.1; SAS Institute, Cary, N.C.). For report presentation, histograms were created for representative weeks 2, 5, 8, and 11 using the Histogram command of SigmaPlot (version 9.0; Systat Software, Richmond, Calif.) with seven bins (bars) per histogram. Normal curves were added to each histogram with the Plot Equation command using the sample mean and sd for each set of data.

Quantile–quantile plots with diagonal distribution reference lines of the data for each week and variable were prepared for initial evaluation using the QQPLOT statement with the NORMAL (MU=EST SIGMA=EST) option under the UNIVARIATE procedure of SAS. For report presentation, QQ plots were prepared with SigmaPlot by plotting the *i*th ordered value against the quantile $\Phi^{-1}[(i - 0.375)/(n + 0.25)]$, where $\Phi^{-1}(\cdot)$ is the inverse cumulative standard normal distribution (*z*-score) and *n* is the number of nonmissing values (in this case, *n* = 100). A diagonal distribution reference line was added to each plot with the Plot Equation command using the sample mean as the intercept and the sample sd as the slope.

Moments (mean, sd, skewness, and kurtosis) were calculated for each week and variable using the UNIVARIATE procedure of SAS. Correlations among the average weekly substrate temperature, pH, and EC were obtained using the CORR procedure of SAS. Randomness of the sample skewness and kurtosis for pH and EC over the 12-week period was assessed with the Wald-Wolfowitz test (runs test) using the “runs.test” function in the “tseries” package of R (The R

Foundation for Statistical Computing, Vienna, Austria). Empirical distribution function test statistics (*D*, *W*², and *A*²), the Shapiro-Wilk regression test statistic, and the *P* values associated with these test statistics under the null hypothesis of normality were determined for each week and variable using the NORMAL option of the UNIVARIATE procedure of SAS. Statistics for tests based on moments [*Z*($\sqrt{b_1}$), *Z*(*b*₂), and *K*²] and their associated *P* values under the null hypothesis of normality were calculated using SAS data statements following the procedures outlined by D’Agostino (1986b).

Results and Discussion

Substrate temperature. Substrate temperature ranged from 14.5 °C to 41.1 °C during the study (Fig. 1). Average daily temperature ranged from 22.8 °C to 30.7 °C, with an overall average temperature of 27.2 °C during the 12-week period. Temperature of the substrate during the study was suitable for release of nutrients into the substrate solution from the topdressing-applied prills of Polyon 17N–2.1P–9.1K + micros. This CRF is listed by the manufacturer as a 365-d nutrient release product at 27 °C.

Extract pH. Except for a pH of 6.40 in week 1, average weekly pH remained in the range of ≈6.60 to 6.80 during the study (Table 1). However, weekly pH values were somewhat less variable during weeks 1 to 7 (Fig. 2), with the sd ranging from 0.068 to 0.085 (Table 1), than in weeks 8 to 12, with the sd ranging from 0.102 to 0.134.

Extract electrical conductivity. Electrical conductivity exhibited a decrease from weeks 1 to 3, followed by an increase through week 9, then another decrease through week 12 (Fig. 3). The initial decrease in EC could be attributed to an initial flushing of non-CRF chemicals from the substrate by the initial irrigations. Weekly EC values were notably less variable during weeks 1 to 5, with the sd ranging from ≈0.011 to 0.030 dS·m⁻¹, than in weeks 6 to 12, with the sd ranging from ≈0.051 to 0.075 dS·m⁻¹.

It appears that nutrients released from the CRF had little influence on the EC of the extract during the first 4 weeks of the study (Fig. 3). This could be the result of the initial time required for the CRF prills to absorb moisture and release dissolved nutrients, initial adsorption of CRF nutrients by the substrate, delayed release of nutrients from the CRF resulting from cooler substrate temperatures early in the study, or a combination of these factors.

Fig. 1. Temperature of substrate (25 pine bark : 18 peat : 7 sand blend) in no. 1 (2.8-L) polyethylene containers on greenhouse benches over a 12-week period (10 June 2005 to 2 Sept. 2005). Temperatures shown are the average readings of sensors buried in the center of eight randomly selected containers of substrate.

Table 1. Weekly mean and sd for pH and electrical conductivity (EC) data obtained from 100 extract samples collected from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) for 12 weeks using the pour-through method.

	Week											
	1	2	3	4	5	6	7	8	9	10	11	12
pH												
Mean	6.40	6.75	6.81	6.75	6.74	6.72	6.62	6.58	6.61	6.71	6.70	6.70
SD	0.084	0.094	0.085	0.071	0.070	0.068	0.078	0.102	0.134	0.112	0.118	0.110
EC (dS·m ⁻¹)												
Mean	0.2366	0.1209	0.1070	0.1333	0.1953	0.3023	0.3800	0.4173	0.4917	0.4139	0.3660	0.3622
SD	0.03030	0.01420	0.01108	0.01754	0.03025	0.05059	0.05211	0.06714	0.07494	0.06235	0.05420	0.06063

Fig. 2. Data points for the pH of extract samples collected weekly from 100 no. 1 (2.8-L) containers of substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) for 12 weeks using the pour-through method, with average weekly means connected by lines.

Fig. 3. Data points for the electrical conductivity (EC) of extract samples collected weekly from 100 no. 1 (2.8-L) containers of substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) for 12 weeks using the pour-through method, with average weekly means connected by lines.

Correlations. Average weekly EC in week i exhibited correlations with the average substrate temperature in weeks i (the 7 d preceding extract collection), $i-1$, $i-2$, $i-3$, and $i-4$ of $r = 0.67, 0.89, 0.92, 0.86$, and 0.70 respectively. (For example, average weekly EC in weeks 3 through 12 exhibited a correlation with the average substrate temperature of the corresponding 7-d periods

2 weeks before extraction of $r = 0.92$.) This pattern suggests that nutrient release from the CRF, which is dependent on substrate temperature, could be more dependent on temperature in the second to fourth weeks preceding extraction than on temperature in the week immediately preceding extraction. Correlations between average weekly pH and time-lagged substrate temperature were

weaker than for average weekly EC and time-lagged substrate temperature. There were no strong correlations between average weekly pH and average weekly EC.

The sd of the weekly EC data (Table 1) was highly and positively correlated with average weekly EC ($r = 0.987$), and also exhibited correlations similar in value and pattern with time-lagged average weekly substrate temperature. This suggests the possibility of greater variability in nutrient release from the CRF prills into the substrate solution with greater nutrient release. In addition, variability (sd) of the weekly pH values in week i exhibited correlations with the average weekly EC in weeks i , $i-1$, $i-2$, $i-3$, and $i-4$ of $r = 0.64, 0.82, 0.89, 0.81$, and 0.56 respectively. This suggests that EC could somehow be influencing variability in pH, without influencing average weekly pH.

It must be emphasized that temperature, pH, and EC were all observed, not controlled, variables in this study. Therefore, direct dependence cannot be established among these variables based on the current data.

Distribution of pH. Histograms suggested no gross departures from normality for the distribution of pH data values, with the graphs being relatively symmetrical for each week of the study period (Fig. 4A–D). Near-normality was also reflected by the QQ plots with the relative linearity of the plotted points (Fig. 5A–D). Measures of skewness and kurtosis of the sample distributions varied with relatively small positive and negative values 0 over the 12-week period (Fig. 6A–B), with the variation being random (Table 2), suggesting that near-normality was typical for this variable throughout the study, because a perfectly normal distribution has skewness and kurtosis values of 0. (It should be noted that an alternate formula for the calculation of kurtosis provides a value of 3 for a perfectly normal distribution. Subtraction of 3 from the value provided by this alternative formula is the convention used by SAS for calculation of sample kurtosis.)

Among the EDF tests for normality, significant ($P \leq 0.05$) nonnormality was indicated only in week 8 by the Cramér-von Mises test alone (Table 3). The $Z(b_2)$ statistic indicated nonnormal kurtosis only in week 6; otherwise, the tests based on moments indicated no serious departure from normality. The Shapiro-Wilk test also indicated no significant departure from normality during any week. Overall, graphical and statistical tests indicate that pH values tended to exhibit a fairly normal distribution.

Distribution of 10^{-pH} . Histograms suggested that distributions of the transformed variable 10^{-pH} were consistently skewed to the right throughout the study (Fig. 4E–H). This was also evident in the curvature exhibited in the QQ plots, with a right-skewed distribution indicated by the plotted points starting above the normal distribution reference line, dipping below the line, and finishing above the line (Fig. 5E–H). Measures of skewness of the sample distributions were all positive and relatively large in

Fig. 4. Histograms displaying the distribution of five variables [pH, $10^{-\text{pH}}$, $\ln(\text{pH})$, electrical conductivity (EC), and $\ln(\text{EC})$] for four representative weeks of a 12-week study, along with comparative normal curves (plotted using the sample mean and SD for each week and variable). Measures of pH and EC were obtained from 100 extract samples collected weekly from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) using the pour-through method.

magnitude (Fig. 6C), and were clearly nonrandom about zero during the study (Table 2), again indicating consistently right-skewed distributions. Measures of kurtosis varied from small to large in magnitude, but the

variation did not exhibit significant nonrandomness about zero over the 12-week study. Kurtosis was most often positive (Fig. 6D), indicating distributions that are more peaked than a perfectly normal distribution.

The Kolmogorov-Smirnov test, Cramér-von Mises test, and Anderson-Darling test indicated significant departures from normality at the 0.05 significance level for 8, 4, and 5 weeks respectively during the 12-week

Fig. 5. Quantile–quantile plots for five variables [pH, $10^{-\text{pH}}$, $\ln(\text{pH})$, electrical conductivity (EC), and $\ln(\text{EC})$] for four representative weeks of a 12-week study, along with diagonal normal distribution lines (plotted using the sample mean and sd for each week and variable). Measures of pH and EC were obtained from 100 extract samples collected weekly from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) using the pour-through method.

Fig. 6. Bar charts displaying weekly sample skewness (left) and kurtosis (right) for five variables [pH, $10^{-\text{pH}}$, $\ln(\text{pH})$, electrical conductivity (EC), and $\ln(\text{EC})$] in a 12-week study. Measures of pH and EC were obtained from 100 extract samples collected weekly from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) using the pour-through method.

study period, whereas the $Z(\sqrt{b_1})$, $Z(b_2)$, and K^2 statistics indicated significant departures from normality for 10, 3, and 9 weeks respectively (Table 3). The Shapiro-Wilk regression test indicated significant nonnormality in most weeks. Results indicate that transformation of the variable pH to the variable $10^{-\text{pH}}$ (to approximate the hydrogen ion concentration, or activity) would be inappropriate when a near-normal variable is required.

Distribution of $\ln(\text{pH})$. Histograms suggested that distributions of the data values for

the transformed variable $\ln(\text{pH})$ were slightly skewed to the left or the right in some weeks, but showed no skewness in other weeks (Fig. 4I–L). Near-normality was indicated by the relative linearity of plotted points in the QQ plots (Fig. 5I–L). Similar to results for the original pH variable, sample skewness and kurtosis for this transformed variable varied with relatively small positive and negative values about zero over the 12-week study (Fig. 6E–F), the variation being random about zero (Table 2). As with results for the pH variable, formal goodness-of-fit statistics

Table 2. *P* values for the null hypothesis of H_0 : randomness of weekly sample skewness about zero over a 12-week period (vs. H_1 : nonrandomness) and the null hypothesis of H_0 : randomness of weekly sample kurtosis about zero over a 12-week period (vs. H_1 : nonrandomness).

Variable	<i>P</i> value
Skewness	
pH	1.000
$10^{-\text{pH}}$	<0.001
$\ln(\text{pH})$	0.252
EC	0.077
$\ln(\text{EC})$	0.021
Kurtosis	
pH	0.466
$10^{-\text{pH}}$	0.210
$\ln(\text{pH})$	0.466
EC	0.917
$\ln(\text{EC})$	1.000

P values are based on the Wald-Wolfowitz test (runs test) for sample skewness and kurtosis measures for the variables pH and electrical conductivity (EC), and the transformed variables $10^{-\text{pH}}$, $\ln(\text{pH})$, and $\ln(\text{EC})$. Measures of pH and EC were obtained from 100 extract samples collected weekly from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) using the pour-through method.

for the $\ln(\text{pH})$ variable indicated no significant departure from normality (Table 3). However, there appears to be no advantage gained by using the transformed variable $\ln(\text{pH})$, given the near-normality of the original variable, pH.

Distribution of EC. Histograms suggested the distributions of the EC data values to be slightly skewed to the right during the first 5 weeks of the study, but relatively symmetrical with no gross departures from normality during the subsequent 7 weeks (Fig. 4M–P). Quantile–quantile plots also suggested right-skewed distributions during the first 5 weeks, but near-normality during the subsequent 7 weeks (Fig. 5M–P). Values of sample skewness were positive, but not large in magnitude, during the first 5 weeks, whereas small positive and negative values followed during the subsequent 7 weeks (Fig. 6G). There was slight indication of nonrandomness of the skewness about zero over the study period (Table 2). Values for kurtosis were mostly small and varied between positive and negative (Fig. 6H), with no indication of nonrandomness about zero (Table 2).

The Kolmogorov-Smirnov test indicated significant departures from normality in weeks 1, 2, and 4, whereas the Cramér-von Mises test, Anderson-Darling test, and Shapiro-Wilk regression test indicated significant departures from normality in weeks 2 and 4 (Table 3). From week 5 onward, goodness-of-fit tests indicated no significant departures from normality. Given that the means and variability (SD) of EC values were lowest during weeks 2 to 4 of the study, slightly greater nutrient release from the CRF into substrate solution in a few containers of substrate (perhaps because of an occasional broken CRF prill) during these 3 weeks could

Table 3. *P* values for the null hypothesis of normality for the distributions of the variables pH, $10^{-\text{pH}}$, $\ln(\text{pH})$, electrical conductivity (EC), and $\ln(\text{EC})$ based on goodness-of-fit test statistics [Kolmogorov-Smirnov statistic (*D*), Cramér-von Mises statistic (W^2), Anderson-Darling statistic (A^2), D'Agostino $Z(\sqrt{b_1})$ statistic, Anscombe and Glynn statistic $Z(b_2)$, D'Agostino-Pearson chi-square statistic (K^2), and Shapiro-Wilk statistic (*W*)].

Statistic	Week											
	1	2	3	4	5	6	7	8	9	10	11	12
pH												
<i>D</i>	>0.150	0.091	>0.150	>0.150	>0.150	>0.150	>0.150	0.064	>0.150	0.080	>0.150	>0.150
W^2	0.173	0.115	0.244	0.231	>0.250	>0.250	0.169	0.038	>0.250	0.054	>0.250	>0.250
A^2	0.236	0.128	>0.250	0.199	>0.250	>0.250	0.145	0.055	>0.250	0.088	>0.250	>0.250
$Z(\sqrt{b_1})$	0.318	0.561	1.000	0.122	0.230	0.819	0.928	0.319	0.117	0.442	0.309	0.147
$Z(b_2)$	0.401	0.285	0.481	0.444	0.643	0.040	0.343	0.965	0.849	0.680	0.513	0.985
K^2	0.427	0.477	0.780	0.226	0.437	0.119	0.636	0.608	0.288	0.683	0.481	0.349
<i>W</i>	0.504	0.314	0.351	0.127	0.522	0.247	0.303	0.185	0.380	0.325	0.595	0.353
$10^{-\text{pH}}$												
<i>D</i>	<0.010	0.035	0.140	0.020	>0.150	>0.150	0.041	>0.150	0.047	0.017	0.109	<0.010
W^2	<0.005	0.066	0.135	0.011	0.131	0.245	0.132	>0.250	0.225	0.042	>0.250	<0.005
A^2	<0.005	0.025	0.070	<0.005	0.055	0.200	0.061	0.184	>0.250	0.030	0.201	<0.005
$Z(\sqrt{b_1})$	0.001	0.008	0.048	0.004	0.002	0.295	0.006	0.063	0.084	0.011	0.015	0.000
$Z(b_2)$	0.053	0.275	0.800	0.495	0.030	0.089	0.022	0.264	0.834	0.083	0.127	0.031
K^2	0.001	0.017	0.138	0.011	0.001	0.136	0.002	0.096	0.219	0.009	0.016	0.000
<i>W</i>	0.001	0.007	0.029	0.002	0.005	0.121	0.008	0.057	0.285	0.015	0.039	0.000
$\ln(\text{pH})$												
<i>D</i>	>0.150	0.086	>0.150	>0.150	>0.150	>0.150	>0.150	0.084	>0.150	0.100	>0.150	>0.150
W^2	0.141	0.123	>0.250	0.207	>0.250	>0.250	0.191	0.050	>0.250	0.070	>0.250	>0.250
A^2	0.199	0.129	>0.250	0.169	>0.250	>0.250	0.159	0.076	>0.250	0.104	>0.250	>0.250
$Z(\sqrt{b_1})$	0.240	0.476	0.897	0.101	0.184	0.885	0.791	0.413	0.177	0.578	0.430	0.104
$Z(b_2)$	0.381	0.332	0.489	0.496	0.577	0.039	0.315	0.962	0.949	0.679	0.549	0.893
K^2	0.341	0.485	0.781	0.207	0.355	0.118	0.583	0.715	0.402	0.787	0.612	0.265
<i>W</i>	0.424	0.291	0.347	0.104	0.454	0.253	0.295	0.224	0.531	0.373	0.691	0.257
EC												
<i>D</i>	0.043	0.029	0.061	0.017	>0.150	>0.150	>0.150	>0.150	>0.150	>0.150	>0.150	>0.150
W^2	0.080	0.030	0.248	0.013	0.228	>0.250	>0.250	>0.250	0.083	>0.250	>0.250	>0.250
A^2	0.091	0.026	>0.250	0.014	0.205	>0.250	>0.250	>0.250	0.098	>0.250	>0.250	>0.250
$Z(\sqrt{b_1})$	0.078	0.073	0.153	0.056	0.067	0.959	0.172	0.322	0.373	0.681	0.748	0.452
$Z(b_2)$	0.141	0.317	0.545	0.767	0.646	0.571	0.848	0.754	0.231	0.689	0.863	0.431
K^2	0.071	0.122	0.300	0.154	0.168	0.850	0.386	0.583	0.328	0.848	0.936	0.552
<i>W</i>	0.104	0.028	0.462	0.026	0.242	0.725	0.391	0.483	0.224	0.740	0.886	0.618
$\ln(\text{EC})$												
<i>D</i>	>0.150	>0.150	>0.150	>0.150	>0.150	>0.150	0.123	>0.150	0.011	>0.150	0.036	<0.010
W^2	0.167	0.191	>0.250	0.232	>0.250	0.233	0.022	0.096	<0.005	0.238	0.097	0.011
A^2	0.194	0.170	>0.250	0.246	>0.250	0.101	0.010	0.038	<0.005	>0.250	0.144	0.006
$Z(\sqrt{b_1})$	0.905	0.385	0.891	0.517	0.951	0.025	0.006	0.006	0.028	0.228	0.155	0.003
$Z(b_2)$	0.313	0.079	0.683	0.623	0.915	0.257	0.460	0.258	0.601	0.775	0.885	0.098
K^2	0.597	0.146	0.912	0.719	0.992	0.042	0.018	0.012	0.078	0.464	0.361	0.003
<i>W</i>	0.396	0.163	0.887	0.304	0.958	0.051	0.008	0.008	0.011	0.421	0.407	0.005

Values for pH and EC were determined from 100 extract samples collected weekly over 12 weeks from a container substrate (pine bark, peat, and sand amended with calcium sulfate and top-dressed with controlled-release fertilizer) using the pour-through method.

account for the right-skewed distributions of the data values. Overall, graphical and statistical tests indicate that extract EC values tended to exhibit a fairly normal distribution, particularly when nutrient release from the CRF is underway.

Distribution of $\ln(\text{EC})$. Histograms suggested no gross departures from normality for the distribution of the transformed data values during the first 5 weeks of the study, but a consistent skewing to the left during the subsequent 7 weeks of the study (Fig. 4Q–T). Quantile–quantile plots also indicated near-normality during the first 5 weeks, but left-skewed distributions in the subsequent 7 weeks were indicated by the curvature of the plotted points starting below the normal distribution reference line, arching above the line, and finishing below the line (Fig. 5Q–T). Values for sample skewness were moderate in magnitude and positive during the last 7 weeks of the study, (Fig. 6I) and nonrandom about zero over the study period (Table 2), whereas values for sample kurtosis were mostly small and varied between positive and negative (Fig. 6J), but were random

about zero (Table 2). Goodness-of-fit statistics indicated no significant departures from normality during weeks 1 through 5 and week 10, whereas significant departures from normality were indicated by one or more goodness-of-fit statistics during the other 6 weeks (Table 3). Overall, data values for the transformed variable $\ln(\text{EC})$ appear to deviate substantially from a normal distribution.

Conclusion

Data values for both pH and EC of extract obtained using the pour-through method appear to follow near-normal distributions, without the need for any transformation of these variables, making the data suitable for analysis and development of statistical inferences using linear models, including ANOVA and linear regression analysis. This conclusion, drawn from analysis of a large, uniform sample, can also lend support to an assumption of normality in experimental studies of a similar nature in which analysis of observations or model residuals may suggest that there is not a significant

deviation from normality, but may be too limited in number to draw a definite conclusion.

Although results from this study indicate that data values for pH and EC of extract obtained using the pour-through method may be analyzed with linear models without transformation of the data values, it remains advisable to run diagnostic procedures with new data to check for normality and validity of other model assumptions. Both graphical methods and formal statistical tests are available for this purpose (Neter et al., 1996), including those discussed earlier for assessing normality. An indication of a lack of normality in data or residuals when normality is expected could be the result of causes such as missing terms in the statistical model, measurement errors, or a lack of uniformity among the experimental units used in a study. Nonconstancy of the error variance may call for use of weighted least squares. Nonindependence of the error terms, as can occur in time series analysis, may call for use of a model that accounts for correlated error terms.

No single goodness-of-fit test is applicable in every situation for testing normality or

deviations from normality (D'Agostino, 1986b). Use of both graphical techniques and formal tests together can be more informative than use of either method of evaluation or any single test alone. Additional caution in assessing the results of these tests is warranted when sample sizes are small. With the exception of the Kolmogorov-Smirnov test, the formal EDF tests, moment tests, and regression tests used in this study have been found to be useful as general tests of normality or for testing specific departures from normality, such as nonnormal skewness and kurtosis. The Kolmogorov-Smirnov test, although often available in statistical software packages, has less power than these other formal tests.

Although not a primary objective of this study, analysis of the weekly means and sds of pH and EC provided supplemental information regarding the relative stability of pH after the first week (Fig. 2) and an indication of week-to-week nutrient availability based on EC data (Fig. 3). Measures of sds can also be useful in calculating sample sizes for similar studies in the future. (Determination of sample size also depends on other considerations, such as the desired power, level of significance, and magnitude of the difference between treatments that the researcher wishes to detect in a two-sample study.) In addition, the variability of pH and EC data noted during the study support the practice of collecting multiple samples when monitoring the soil solution using the pour-through method.

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