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A Data-driven Approach for Generating Leaf Tissue Nutrient Interpretation Ranges for Greenhouse Lettuce

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Abstract. **In the absence of controlled sufficiency studies, foliar interpretations for many horticultural crops are based on survey concentrations from small data sets. In addition, both survey and sufficiency ranges provide little interpretation regarding zones that are above or below the concentration range deemed "sufficient." While providing a critical initial set of ranges, it was based on a limited set of data and therefore improvements in interpretation of data are needed. This study presents a novel method based on 1950 data points to create data-driven nutrient interpretation ranges by fitting models to provide more refined ranges of deficient (lowest 2.5%), low (2.5% to 25%), sufficient (25% to 75%), high (75% to 97.5%), and excessive (highest 2.5%). Data were analyzed by fitting Normal, Gamma, and Weibull distributions. Corresponding *P* values were calculated based on the Shapiro-Wilk test for normality for the Normal and Gamma distributions, and the Kolmogorov-Smirnov test was used for the Weibull distribution. The optimal distribution was selected based on the lowest Bayesian Information Criterion (BIC) value and visual fitness. The Weibull distribution best represented nitrogen, phosphorus, potassium, calcium, manganese, zinc, and copper, and the Gamma distribution best represented magnesium, sulfur, iron, and boron. Using the selected distributions, we propose a refined set of nutrient evaluation ranges for greenhouse-grown lettuce. These refined standards will aid growers and technical specialists in more accurately interpreting leaf tissue sample data.**

Monitoring leaf tissue nutrient concentration is crucial for assessing the nutritional status of plants and diagnosing nutrient deficiencies or toxicities. Nutrient concentration data aid in evaluating the effectiveness of fertilizer applications and optimizing nutrient management strategies. The optimal concentrations of nutrients in leaf tissue varies depending on plant species and growth stage (Bryson et al. 2014; Reuter and Robinson 1997). This requires development of species-specific interpretative ranges for each essential element, which is challenging due to the number of specialty crops being grown in horticulture production.

Lettuce (*Lactuca sativa* L.) is the most common hydroponically grown crop (Abbey et al. 2019). Researchers have published descriptions of deficiency symptoms for individual elements and the critical nutrient concentrations at which these symptoms appear (Bryson et al. 2014; Henry et al. 2018; Van Eysinga and Smilde 1981). Providing nutrient fertility rates to promote optimum plant growth or yield without resulting in luxury consumption is an economic priority for growers. Veazie et al. (2022) determined the impact of individual macroelement fertility concentrations on lettuce growth and how fertility requirements varied throughout the production cycle. These studies provided insight into the optimal leaf nutrient concentrations for lettuce, yet with this crop being of such importance in the industry, further refinement of nutritional ranges is needed.

The use of plant analysis for determining the nutrient status of a plant was first proposed by Hall (1905) and Hoffer (1926) proposed the application of leaf tissue analysis for diagnostic purposes. For most specialty crops, the Survey Approach (SA) of sampling a specific plant part in grower fields to establish an overall nutritional norm for a crop (Fullmer 1957) or focusing on healthy looking plants to provide a baseline set of leaf tissue nutrient standards for actively growing, healthy plants (Bryson et al. 2014) was an important initial step. Although the SA data were limited in scope and sample number, they provided an initial baseline set of values for use in evaluating tissue samples submitted by growers to analytical laboratories. Today, many analytical laboratories in the United States rely on these SA values when evaluating specialty crop samples.

More robust evaluation standards that account for varying growing conditions and plant development stage were needed. Expansion from the SA has led to several refined evaluation methods including the Critical Value Approach (CVA) (Ulrich 1948), the Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1973), and Sufficiency Range Approach (SRA) (Soltanpour et al. 1995). All three approaches have advantages and limitations when it comes to evaluating and diagnosing plant nutrient status.

The CVA was an advancement step in the evaluation of leaf tissue nutrient samples compared with SA. It evaluates leaf nutrient concentrations against preestablished critical values or thresholds, which are typically set at no less than 90% to 95% of the maximum yield (Jones et al. 1990; Richards and Bevege 1972; Ulrich 1948). Critical values used in the CVA must be species specific and adjusted for growth stages or regional variations. An advantage of the CVA is its relative simplicity to understand and implement, making it accessible to a wide range of users, including growers and agronomists. The CVA provides a binary assessment of nutrient concentrations (deficient or sufficient) based on fixed thresholds, but the lack of nuanced information about the severity of a nutrient imbalance or its impact on plant performance limits this approach (Caron and Parent 1989). This may lead to an incomplete understanding of the overall nutrient status of a plant. In addition, the primary focus of the CVA is on the critical point between a deficient and sufficient range but it does not provide information about the upper end of the excessive range or toxic nutrient threshold.

The DRIS method is the most extensive tool used in evaluating the status of leaf tissue nutrient values (Beaufils 1973; Partelli et al. 2018). It is viewed as the complementary interpretation of SRA data. The DRIS relies on calculated indexes for each nutrient, which are functions that express the concentration ratio of each element. DRIS identifies specific nutrient imbalances, providing insights into the nature and severity of nutrient limitations or excesses. DRIS standards have been developed for numerous species including banana [(*Musa* sp.) (Villaseñor et al. 2020)], oil palm [(*Elaeis guineensis* Jacq.) (Matos et al. 2017)], mandarin orange [(*Citrus reticulata* Blanco) (Srivastava and Singh 2008)], pineapple [(*Ananas comosus* L.) (Sema et al. 2010)], potato [(*Solanum tuberosum* L.) (Oliveira et al. 2020)], and tomato [(*Solanum lycopersicum* L.) (Scucuglia and Creste 2014)]. Limitations of DRIS include the need for a well-established reference population recommended to number several thousand observations, extensive nutrient ratios, and yield data (Marschner 1995), which may not always be readily available, particularly for specialty crops or specific geographical regions. Yield data are used to determine the maximum output, but with many ornamental species, maximal growth may not be the economic objective. For example, a higher number of smaller plants grown per unit area of greenhouse bench space could be more profitable. In addition, DRIS data compilation involves complex calculations and statistical procedures, which is time-consuming. Soltanpour et al. (1995) found SRA to be more robust than DRIS in diagnosing nutrient disorders in corn (*Zea mays* L.). Luo et al. (2022) also evaluated the suitability of CVA, SRA, and DRIS on diagnosing litchi (*Litchi chinensis* Sonn.) foliar tissue samples. They concluded that the SRA had a higher degree of accuracy than CVA or DRIS. Over time, as datasets expand, the complementary analysis of DRIS will likely improve, increase in accuracy, and expand in usage with specialty crops.

The SRA provides an assessment of individual nutrient concentrations (deficient or sufficient) but does not explicitly account for interactions between nutrients that DRIS provides. Therefore, nutrient imbalances or interactions that may affect plant performance are not considered in the interpretation. Sufficiency ranges may vary depending on species, growth stage, and plant part making it essential to have crop-specific sufficiency range guidelines. The availability of larger crop datasets would aid in overcoming this limitation. It has the advantage of simplicity because it is relatively straightforward to understand, making it appropriate for a wide range of data. Sufficiency ranges are based on extensive research and field observations. The SRA evolved out of the CVA when it was determined that there were too many independent variables to have a specific critical value and a critical range would be more practical.

The SRA has been used to increase the number of crops for which recommended leaf tissue ranges have been defined, including numerous ornamental species such as coral bells [(*Heuchera hybrida* L.) (Owen 2019a)], perennial hibiscus [(*Hibiscus hybrid* L.) (Owen 2019b)], osteospermum [(*Osteospermum ecklonis* DC) (Papineau and Krug 2014), geranium [(*Pelargonium ×hortorum* Bailey) (Krug et al. 2010), and Russian sage [(*Perovskia* sp.) (Owen 2020)]. These studies were based on the maximization of growth as the determining factor for establishing the tissue standard ranges. These studies offer an improvement of recommended leaf tissue standards over what is currently available with the SA method. However, these studies generally rely on a smaller dataset ($\sim$n < 200) and do not differentiate between deficient and low ranges and high and excessive ranges.

When diagnosing nutrient disorders, knowing a critical nutrient concentration aids in confirming observed foliar symptoms. First reported in the 1940s, induced nutrient deficiency studies were conducted using high-quality salts where single nutrients were withheld to determine critical nutrient deficiency concentrations (Ulrich 1948). Extensive development of these ranges along with photographic documentation of symptomology has been completed for 26 specialty species by Gibson et al. (2007) and others. The more challenging aspect is determining excessive or toxic levels of a nutrient. Although uptake curves have been presented that include the upper excess and toxic zones (Ulrich 1948), data to support the actual nutrient concentrations that denote those values are lacking. Quality characteristics can be used to determine when nutrients are excessive. Ulrich and Hills (1990) recommended nitrogen fertilization rates based on maximizing sugarbeet (*Beta vulgaris* var. *saccharifera* L.) sugar concentration instead of where plant mass was highest. For toxicities, the visual symptomology for micronutrients can be induced by adding toxic levels of that element. In contrast, macronutrient excesses rarely manifest into actual symptomology of the nutrient being manipulated, but instead interactions can create antagonisms with uptake of other elements, such as excessive phosphorus levels inducing an iron deficiency or when potassium is in excess, it may limit uptake of calcium or magnesium (Bryson et al. 2014; Ulrich 1948). Because of the lack of available published scientific methods or limited data, agronomists in the southeastern United States leaf tissue laboratories use an evaluation method that multiplied the upper sufficiency value by 1.5 for the macroelements and a 2X value for the micronutrients to established the boundary between high and toxic levels of an element (Hicks K, personal communication). The use of a data-driven approach offers the opportunity of improved refinement of the upper nutrient ranges.

To improve the level of interpretation of the SRA, data from grower samples sent to analytical laboratories can be used to provide

Table 1. Sources of lettuce leaf tissue nutrient data used in the development of the sufficiency range approach (SRA) distribution model.

Source	Sample size	Sample type	Citation
North Carolina Department of Agriculture Laboratory	395	Diagnostic	Grower submitted diagnostic and predictive samples, unpublished
J.R. Peters Laboratory	292	Diagnostic	Grower submitted diagnostic and predictive samples, unpublished
North Carolina State University	386	Research[i]	Veazie et al. (2022)
North Carolina State University	114	Research[ii]	Henry et al. (2018)
North Carolina State University	45	Research[iii]	Henry et al. (2019)
USDA-ARS	48	Research[iv]	Meng et al. (2020)
USDA-ARS	15	Research[iv]	Cultivar evaluation for indoor leafy greens production, unpublished
Michigan State University	379	Research[v]	Improving color and phenolic content of leafy greens and microgreens with end of production lighting and chilling treatments, unpublished
Cornell University	276	Research[vi]	Eylands (2023)

[i] Veazie et al. (2022).
[ii] Henry et al. (2018).
[iii] Henry et al. (2019).
[iv] Meng et al. (2020).
[v] Gerovac et al. (2016).
[vi] Eylands (2023).
USDA-ARS 5 US Department of Agriculture-Agricultural Research Service.
Citations for leaf tissue analysis methods used for data.

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Table 2. Summary of lettuce leaf tissue reference values from prior research, defining deficient, sufficient, or toxicity concentrations, which were used for comparison with this research project.

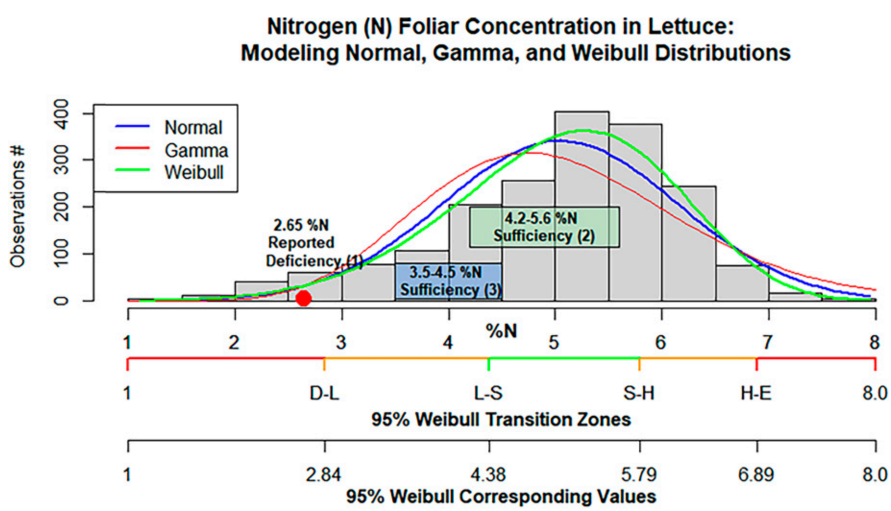
Element	Unit	Deficient[i]	Deficient[i,ii]	Healthy[i,ii]	Sufficient[ii]	Sufficient[i]	Toxic[i,ii]	Approximate excess or toxicity[iii]
Nitrogen (N)	%	2.65	—	2.10–5.60	4.20–5.60	3.50–4.50	—	—
Phosphorus (P)	%	0.13	<0.59	0.40–0.92	0.62–0.77	0.40–0.80	—	—
Potassium (K)	%	0.79	<3.91	3.91–9.78	7.82–13.68	5.50–6.20	—	—
Calcium (Ca)	%	0.29	<0.80	0.88–2.0	0.80–1.20	2.00–2.80	—	—
Magnesium (Mg)	%	0.07	<0.29	0.36–0.90	0.24–0.73	0.60–0.80	—	—
Sulfur (S)	%	0.09	<0.25?	0.19–0.41	0.26–0.32	—	—	—
Iron (Fe)	mg/kg	55.1	—	55.9–558.5	168–223	—	—	>500
Boron (B)	mg/kg	7.7	<21.6	21.6–64.9	32–43	25–60	>54.0–64.9	50–200
Manganese (Mn)	mg/kg	6.88	<22.0	30.2–197.8	55–110	11–250	>197.8–302.5	300–500
Zinc (Zn)	mg/kg	13.72	<26.2	32.7–196.1	32–196	20–250	>392.3	100–400
Copper (Cu)	mg/kg	1.42	<2.54	5.1–17.2	6–16	5–25	>21.0	20–100
Source		Henry et al. (2018)	Van Eysinga and Smilde (1981)	Van Eysinga and Smilde (1981)	Bryson et al. (2014)	Jones (2005)	Van Eysinga and Smilde (1981)	Jones (2005)

[i] Values from greenhouse-based studies.
[ii] Values from field-based studies.
[iii] Approximate values based on generalized ranges for numerous species.

a more robust dataset. The inclusion of grower data with research data increases the number of observations available for data analysis, as well as provides a broader distribution curve. From that distribution curve, further categorization of thresholds for deficient, low, high, and excessive tissue nutrient concentrations in addition to a refined sufficiency range can be determined. As a result, SRA can provide a well-established framework for interpreting nutrient concentrations.

To develop an interpretation model with SRA that includes deficient, low, sufficient, high, and excessive ranges, the optimal distribution curve must be identified. Most data tend to be skewed, which makes the Normal distribution curve less suitable. Two models that account for possible skewness in distribution curves are Gamma and Weibull (Cera et al. 2022; Mhango et al. 2021; Slaton et al. 2021; Weibull 1951). The evaluation of all three models is necessary to determine the one that most accurately depicts the data.

For the numerous specialty edible and ornamental crops in which limited nutrient data exist, the SRA offers the advantage of being able to use both research experimental data and plant tissue laboratory sample data to create a robust distribution curve. This provides more refined and expanded interpretation standards than what is available with the SA and provides an improved reference dataset for use with DRIS analyses. The objective of this study was to evaluate the suitability of SRA for predicting the nutritional status of lettuce, the most common hydroponic crop, lettuce based on Normal, Gamma, and Weibull distribution curves.



Distribution	BIC
Normal[1]	5748.35
Gamma[2]	6065.861
Weibull[2]	5606.174

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 1. Nitrogen foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).

Materials and Methods

Sample collection. Foliar tissue analysis samples were obtained from controlled university research studies from across the United States and supplemented with samples from public and commercial analytical laboratories. The samples only included lettuce grown in controlled environments (greenhouse and growth rooms) (n = 1950) (Table 1). Leaf tissue samples were analyzed for each study based on procedures cited. With the short production time used with hydroponically grown lettuce, only one set of nutrient standards for the entire ∼30- to 40-d production cycle was developed.

Statistical analysis. Data were statistically analyzed using R (v. 4.1.1; R Foundation for Statistical Computing, Vienna, Austria). Each element was modeled independently and outliers that were extremely excessive (greater than what is biologically feasible or a significant break in the population) of any other samples were removed before further analysis. Data were analyzed by fitting Normal, Gamma, and Weibull distributions (Cera et al. 2022; Mhango et al. 2021; Slaton et al. 2021; Weibull 1951). Corresponding *P* values were calculated based on the Shapiro-Wilk test for normality for the Normal and Gamma distributions, and the Kolmogorov-Smirnov test was used for the Weibull distribution. The optimal distribution was selected based on the lowest BIC value and visual fitness. Results were illustrated using ggplot2 (Wickham 2011) in R. The sufficiency range

Table 3. Revised lettuce leaf tissue nutrient interpretation values based on 1950 samples analyzed by the Sufficiency Range Approach.

Element	Unit	Deficient	Low	Sufficient	High	Excessive
Nitrogen (N)	%	<2.84	2.84–4.38	4.38–5.79	5.79–6.89	>6.89
Phosphorus (P)	%	<0.27	0.27–0.58	0.58–0.96	0.96–1.31	>1.31
Potassium (K)	%	<2.93	2.93–5.72	5.72–8.82	8.82–11.55	>11.55
Calcium (Ca)	%	<0.34	0.34–0.79	0.79–1.36	1.36–1.91	>1.91
Magnesium (Mg)	%	<0.15	0.15–0.31	0.31–0.56	0.56–0.90	>0.90
Sulfur (S)	%	<0.11	0.11–0.19	0.19–0.30	0.30–0.45	>0.45
Iron (Fe)	mg/kg	<35.8	35.8–77.6	77.6–148.9	148.9–247.9	>247.9
Boron (B)	mg/kg	<15.3	15.3–25.4	25.4–40.3	40.3–58.9	>58.9
Manganese (Mn)	mg/kg	<18.7	18.7–70.7	70.7–167	167–285.1	>285.1
Zinc (Zn)	mg/kg	<12.1	12.1–33.9	33.9–65.9	65.9–99.7	>99.7
Copper (Cu)	mg/kg	<1.5	1.5–4.8	4.8–10.0	10.0–15.9	>15.9

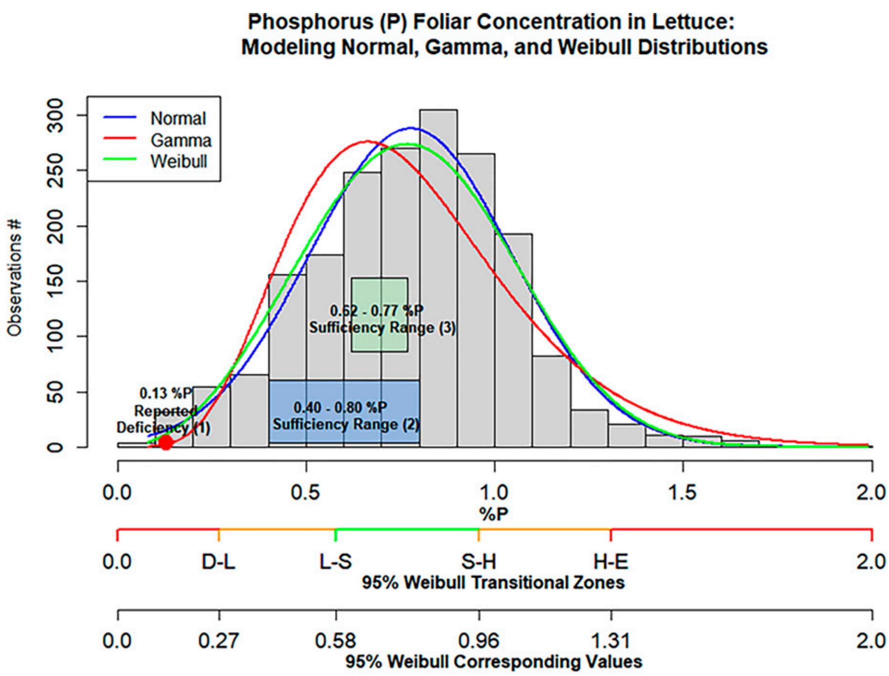
was based on the area between the 0.25 and 0.75 quantiles. The low range corresponded to the range between the lowest 2.5% of the observations and the 0.25 quantile, and the high range was based on the region between the 0.75 quantile and the highest 2.5% of the observations. The deficiency range was established based on the left tail of a 95% distribution (lowest 2.5% of the samples which contained >40 observations), and the excessive range was based on the right tail of a 95% distribution (highest 2.5% of the samples that contained >40 observations). Table 2 contains reference lettuce leaf tissue values from prior research (Bryson et al. 2014; Henry et al. 2018; Jones 2005; Van Eysinga and Smilde 1981) defining deficient, sufficient, or toxicity concentrations and were used to evaluate the results of this study.

Results and Discussion

Nitrogen. Of the three examined models, a Weibull distribution optimally represented nitrogen (N) foliar concentrations, based on having the lowest BIC value and the best visual representation of the tails of the data (Fig. 1, Tables 2 and 3). A recommended sufficiency range of 4.38% to 5.79% N expands the N sufficiency ranges of 4.2% to 5.6% N (Bryson et al. 2014) and 4.8% to 5.5% N (Veazie et al. 2022). In addition, the deficiency value of 2.84% N was similar to the 2.65% N reported by Henry et al. (2018), confirming that <2.84% N is inclusive of previously reported deficiency values. Although N toxicity is rare, ammonium (NH_4^+) toxicity can occur when excessive concentrations are supplied or growing conditions for conversion of NH_4^+ to nitrate (NO_3^-) are not optimal due to low (<20 °C) or excessive (>40 °C) temperatures, waterlogged substrates, or low substrate solution pH (<5.6) (Handreck and Black 2002). Although no N foliar toxicity concentrations have been reported for lettuce, luxury uptake, which constitutes wasteful applications of N, and potential antagonistic relationships with other elements need to be considered. High foliar N concentrations can lead to lower boron (B), copper (Cu), and potassium (K) foliar concentrations (Marschner 1995). Veazie et al. (2022) reported a quadratic plateau regarding N foliar concentration of 5.41% for 8-week-old lettuce grown using an N fertility rate of 111.4 mg·L^{-1} N. The Weibull distribution curve establishes 6.89% N as the boundary between high and excessive concentrations and offers a target value for possible future refinement.

Phosphorus. Phosphorus (P) foliar concentrations were best represented using a Weibull distribution (Fig. 2, Tables 2 and 3). Although a smaller BIC value was achieved by a Normal distribution, the tails were better represented visually by a Weibull distribution. Based on this curve, a recommended sufficiency range of 0.58% to 0.96% P would expand the upper P sufficiency range reported by Jones (2005) and overlap with the P sufficiency range reported by Bryson et al. (2014). In addition, this range includes the plateau of 0.6% P reported by Veazie et al. (2022) after 8 weeks of growth when plants were fertilized with up to 9.86 mg·L^{-1} P. Van Eysinga and Smilde (1981) considered <0.59% P to be deficient, but their recommended range of 0.40% to 0.92% P included that value. The P deficiency foliar concentration threshold of 0.27% P, based on the lowest 2.5% of the observations, was greater than the 0.13% P reported by Henry et al. (2018) and confirms that this suggested deficiency range encompasses previously reported deficient values. This method establishes >1.31% P to be excessive. Although P toxicity values have not been reported in lettuce, P foliar concentrations exceeding 2% can be considered toxic for most species (Marschner, 1995). Excessive P concentrations can antagonize the uptake of Cu, iron (Fe), and zinc (Zn).

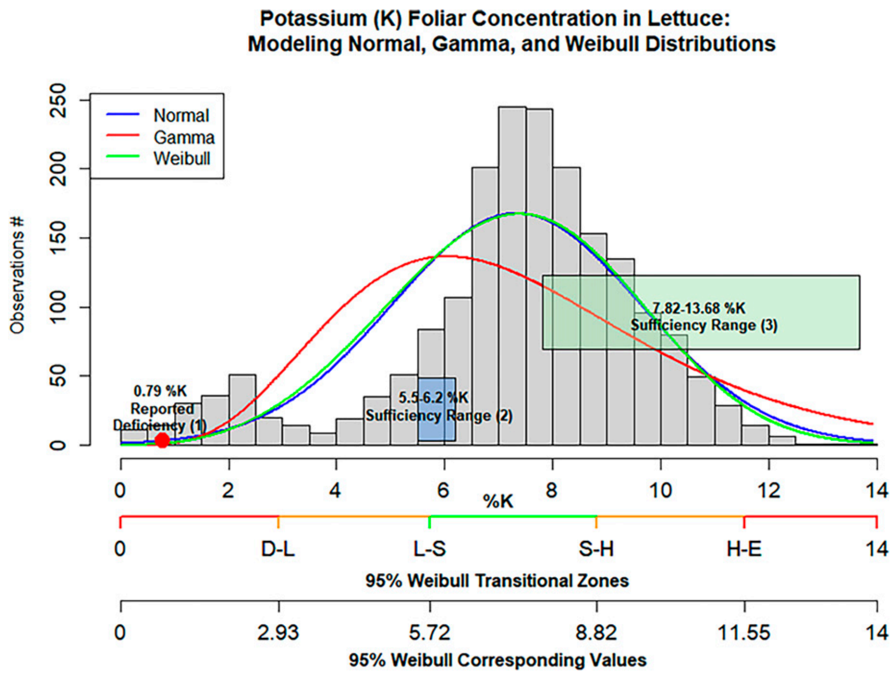
Potassium. Although both the Normal and Weibull distributions yielded similar BIC values, the Weibull distribution better visually represented the right tail of the samples for foliar K concentrations (Fig. 3, Tables 2 and 3). A recommended sufficiency range of 5.72% to 8.82% K increases the lower bound from



Distribution	BIC
Normal[1]	406.45
Gamma[2]	627.58
Weibull[2]	420.84

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 2. Phosphorus foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	8738.943
Gamma[2]	9606.604
Weibull[2]	8867.674

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 3. Potassium foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).

3.91% K (Van Eysinga and Smilde 1981), expands the current recommendation of 5.5% to 6.2% reported by Jones (2005), and lowers the recommended sufficiency range of 7.82% to 13.68% reported by Bryson et al. (2014). A deficiency range of <2.93% K is less than the 3.91% K published by Van Eysinga and Smilde (1981), but encompasses the deficiency values of 0.79% and 1.14% reported by Henry et al. (2018) and Veazie et al. (2022), respectively. The threshold for excessive K was established at 11.55% K. When K supply is abundant, luxury consumption of K will often occur and this luxury consumption should be monitored to limit potential interference of magnesium (Mg) and calcium (Ca) uptake (Marschner 1995).

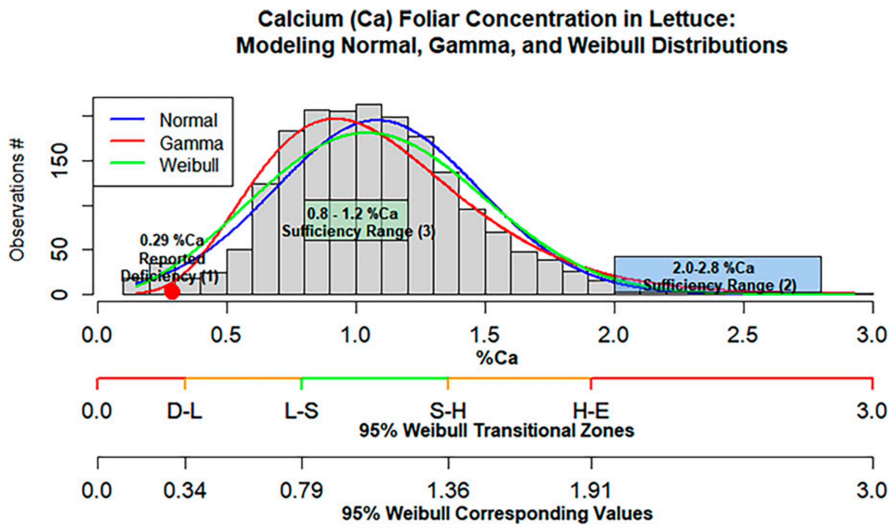
Calcium. Ca foliar concentrations were best represented using a Weibull distribution, which yielded the smallest BIC value of the three models (Fig. 4, Tables 2 and 3). Based on this curve, a recommended sufficiency range of 0.79% to 1.36% Ca would extend the upper end of the current Ca sufficiency range of 0.8% to 1.2% Ca reported by Bryson et al. (2014), but lower the upper range of 0.88% to 2.0% Ca reported by Van Eysinga and Smilde (1981) and 2.0% to 2.8% Ca reported by Jones (2005). The Ca deficiency foliar concentration of 0.34% Ca was slightly greater than the 0.29% Ca reported by Henry et al. (2018), which confirms that this suggested deficiency range encompasses previously reported deficient values. Currently, there are no published Ca excessive or toxicity values for lettuce. However, luxury consumption of Ca can occur when abundant Ca is supplied and this may be reflected in the higher recommended range of 2.0% to 2.8% Ca reported by Jones (2005). Luxury consumption should be monitored for the possibility of interference with P, K, Mg, Fe, B, manganese (Mn), and Zn uptake (Marschner 1995). Using the Weibull distribution, the upper 2.5% of samples set the excessive range threshold at 1.91% Ca (Fig. 4). The proposed excessive range establishes an upper threshold to prevent the occurrence of decreased K and Mg uptake as a result of excessively high Ca foliar concentrations.

Magnesium. When a Gamma distribution was applied to Mg foliar concentrations, it had the lowest BIC value and best represented the tails and the center compared with the other two examined distributions (Fig. 5, Tables 2 and 3). The identified sufficiency range of 0.31% to 0.56% Mg is lower than the current recommendation of 0.6% to 0.8% Mg reported by Jones (2005) and 0.36% to 0.90% Mg listed by Van Eysinga and Smilde (1981), and it is also narrower than the recommended sufficiency range of 0.24% to 0.73% Mg reported by Bryson et al. (2014). A deficiency range of <0.15% Mg encompasses deficiency values of 0.07% and 0.10% Mg reported by Henry et al. (2018) and Veazie et al. (2022), respectively. Magnesium deficiency disrupts the loading of sucrose into the phloem, resulting in carbon accumulation in source leaves (Guo et al. 2016); however, excess leaf tissue Mg can inhibit photosynthesis and plant growth (Rao et al. 1987). Thus, Mg foliar concentrations must be closely monitored to promote optimal plant growth and also avoid antagonisms with K and Ca uptake. This work establishes the first report of 0.90% Mg as the threshold for excessive Mg foliar concentrations in lettuce.

Sulfur. Of the three examined models, a Gamma distribution was determined to optimally represent sulfur (S) foliar concentrations. Although it did not have the lowest BIC value, the model visually best fit the tails (Fig. 6, Tables 2 and 3). A recommended sufficiency range of 0.19% to 0.30% S expands the current S sufficiency range of 0.26% to 0.32% S reported by Bryson et al. (2014), but is narrower than the 0.19% to 0.41% S recommended by Van Eysinga and Smilde (1981). In addition, a deficiency value of 0.11% S was similar to the 0.09% S reported by Henry et al. (2018), confirming that <0.11% S is inclusive of previously reported deficiency values. Currently, there are no reports for excessive or toxic S foliar concentrations of lettuce; however, this distribution establishes 0.45% S as the boundary value between high and excessive levels, offering a target value that may benefit from future refinement.

Iron. Iron foliar concentrations were best represented using a Gamma distribution, which yielded the smallest BIC value of the three models (Fig. 7, Tables 2 and 3). Based on this curve, a recommended sufficiency range of 77.6 to 148.9 $mg \cdot kg^{-1}$ Fe would decrease the current Fe sufficiency range reported by Bryson et al. (2014) of 168 to 223 $mg \cdot kg^{-1}$ Fe. The Fe deficiency foliar concentration of 35.8 $mg \cdot kg^{-1}$ Fe based on the lowest 2.5% of the samples was less than the 55.1 $mg \cdot kg^{-1}$ Fe reported by Henry et al. (2018). Currently, the reported toxic Fe foliar concentration of lettuce is set at >500 $mg \cdot kg^{-1}$ Fe (Jones 2005). The healthy range of 55.9 to 558.5 $mg \cdot kg^{-1}$ Fe reported by Van Eysinga and Smilde (1981) encompasses the entire spectrum recommended in this study, from deficient to excessive, but they also stated that Fe values varied widely and most likely limited their ability to classify Fe leaf concentrations. Our research suggests that the excessive zone begins at 247.9 $mg \cdot kg^{-1}$ Fe.

Boron. The Gamma distribution had the lowest BIC and best represented the tails and the center compared with the other two examined distributions (Fig. 8, Tables 2 and 3). A recommended sufficiency range



Distribution	BIC
Normal[1]	1909.207
Gamma[2]	1932.828
Weibull[2]	1904.996

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 4. Calcium foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).

of 25.4 to 40.3 mg·kg^{-1} B narrows the current recommendations of 25 to 60 mg·kg^{-1} B reported by Jones (2005) and 21.6 to 64.9 mg·kg^{-1} B listed by Van Eysinga and Smilde (1981). It also lowers the recommended sufficiency range of 32 to 43 mg·kg^{-1} B reported by Bryson et al. (2014). A deficiency range of less than 15.3 mg·kg^{-1} B encompasses the deficiency value of 7.7 mg·kg^{-1} B reported by Henry et al. (2018), yet Van Eysinga and Smilde (1981) considered $<$21.6 mg·kg^{-1} B to be deficient. Differences in values may be because B deficiencies can be the result of the lack of a nutrient or due to environmental conditions that limit water and B transpiration in the plant. Currently, excessive B foliar concentrations of lettuce are considered to be concentrations $>$50 to 200 mg·kg^{-1} B (Jones 2005). Van Eysinga and Smilde (1981) considered $>$54 to 64.9 mg·kg^{-1} B to be toxic. This research increases the transition between high and excessive to $>$58.9 mg·kg^{-1} B.

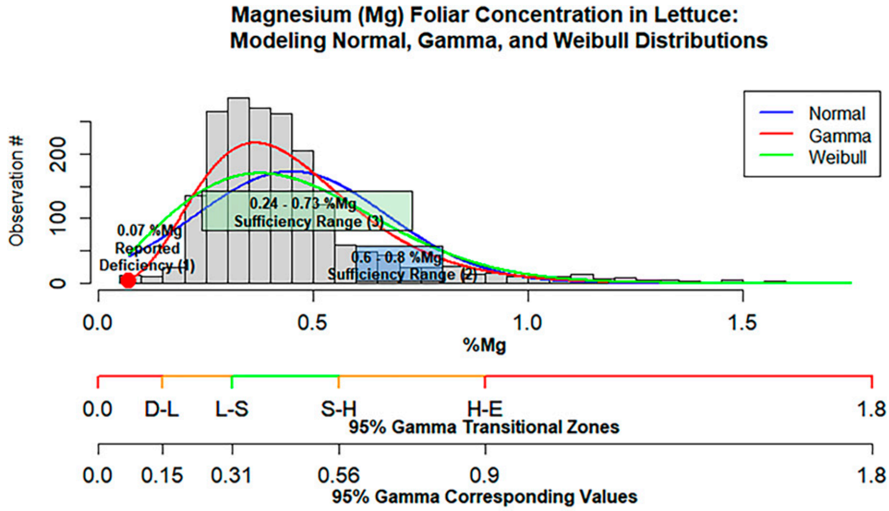
Manganese. Of the three examined models, a Weibull distribution had the lowest BIC and visually represented the samples in the tails the best (Fig. 9, Tables 2 and 3). A recommended sufficiency range of 70.7 to 167.0 mg·kg^{-1} Mn expands the current sufficiency range of 55 to 110 mg·kg^{-1} Mn reported by Bryson et al. (2014) and narrows the range of 11 to 250 mg·kg^{-1} Mn reported by Jones (2005) and the 30.2 to 197.8 mg·kg^{-1} Mn recommended by Van Eysinga and Smilde (1981). In addition, the deficiency threshold of 18.7 mg·kg^{-1} Mn is lower than the $<$22.0 mg·kg^{-1} Mn listed by Van Eysinga and Smilde (1981), yet encompasses the previously reported value of 6.88 mg·kg^{-1} Mn by Henry et al. (2018). Reuter and Robinson (1997) reported toxic Mn foliar concentration for lettuce to be $>$333 mg·kg^{-1} Mn. A wider range was reported by Van Eysinga and Smilde (1981), who considered $>$198 to 302 mg·kg^{-1} Mn to be toxic. Our research decreases the transition between high and excessive zones to $>$285.1 mg·kg^{-1} Mn.

Zinc. Zn foliar concentrations were best represented using a Weibull distribution, which best represented the middle and tails of the observations across all three models even though it did not have the lowest BIC (Fig. 10, Tables 2 and 3). Based on this distribution, a recommended sufficiency range of 33.9 to 65.9 mg·kg^{-1} Zn would narrow the current Zn sufficiency ranges of 32 to 196 (Van Eysinga and Smilde 1981; Bryson et al. 2014) and 20 to 250 mg·kg^{-1} Zn (Jones 2005). The Zn deficiency foliar concentration of 12.1 mg·kg^{-1} Zn based on the lowest 2.5% of the samples was similar to the 13.72 mg·kg^{-1} Zn reported by Henry et al. (2018), but lower than the $<$26.2 mg·kg^{-1} Zn listed by Van Eysinga and Smilde (1981). Currently, reported excessive Zn foliar concentrations of lettuce are $>$96 mg·kg^{-1} Zn (Reuter and Robinson 1997), whereas Van Eysinga and Smilde (1981) considered $>$392.3 mg·kg^{-1} Zn to be toxic concentrations. These previously reported excessive values of Reuter and Robinson (1997) concur with this research, which determined the 97.5 quantile to be 99.7 mg·kg^{-1} Zn.

Copper. The Weibull distribution for Cu concentration had the lowest BIC and best represented the tails and the center compared with the other two examined distributions (Fig. 11, Tables 2 and 3). A recommended sufficiency range of 4.8 to 10 mg·kg^{-1} Cu narrows the current recommendations of 5.1 to 17.2 mg·kg^{-1} (Van Eysinga and Smilde 1981), 5 to 25 mg·kg^{-1} (Jones 2005), and 6 to 16 mg·kg^{-1} Cu (Bryson et al. 2014). A deficiency range of $<$1.5 mg·kg^{-1} Cu encompasses the deficiency value of 1.42 mg·kg^{-1} reported by Henry et al. (2018), but is higher than the $<$2.54 mg·kg^{-1} Cu reported by Van Eysinga and Smilde (1981). Currently, reported toxic Cu foliar concentrations of lettuce are concentrations $>$21 mg·kg^{-1} Cu (Van Eysinga and Smilde 1981) and 20–100 mg·kg^{-1} (Jones 2005). This current research lowers the transition between high and excessive zones to $>$15.9 mg·kg^{-1} Cu.

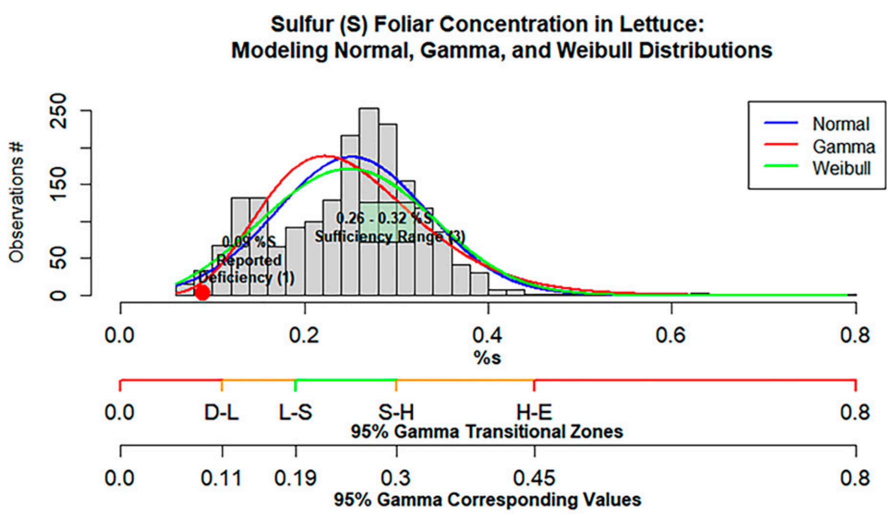
Conclusions

The refinement of leaf tissue nutrient standards is an ongoing process. Prior reported values helped develop initial deficient, sufficient, and in some cases excess ranges. The data used in creating those ranges were limited, thus in many cases, such as deficiency values, they identified a number along a wider continuum, but not the entire zone where deficient values occurred. For diagnosing nutritional problems in lettuce, a more refined system was needed. This study's approach was to use a larger dataset and fit appropriate distribution models using an SRA method to provide more defined ranges beyond the sufficiency zone to also enable the identification of samples that are deficient, low, sufficient, high, or excessive. The establishment of five ranges helps delineate previously reported lower and upper values included in the sufficiency range into more refined zones. These five zones will aid technical specialists and analytical laboratories in more accurately classifying and diagnosing nutritional disorders. By using a dataset primarily composed of controlled experiments and supplemented with testing laboratory samples, it offers the opportunity to create more defined leaf tissue nutrient standards. This is especially important for specialty crops that currently have only survey values available for evaluating laboratory results. Finally, the inclusion of a more robust data set in determining the sufficiency ranges will also be of value in future efforts to establish DRIS indexes.



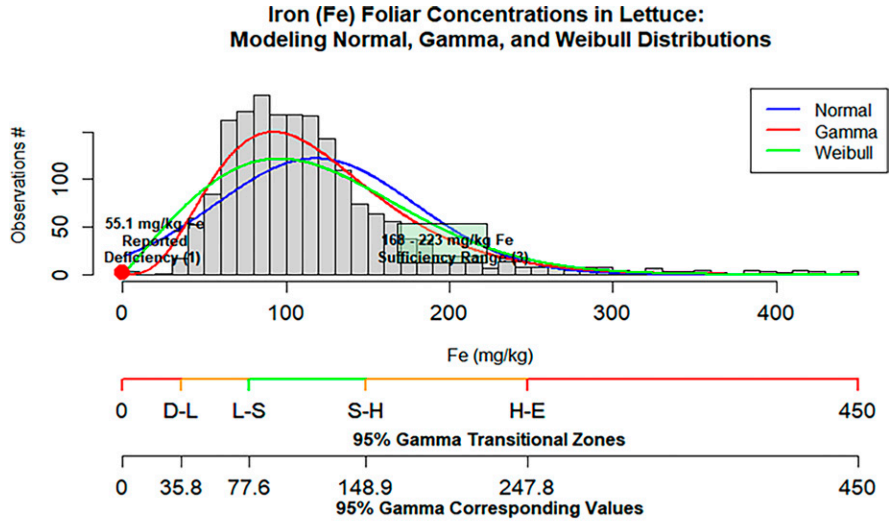
Distribution	BIC
Normal[1]	-286.009
Gamma[2]	-1095.689
Weibull[2]	-679.096
[1]Subjected to Shapiro-Wilk normality test [2]Subjected to Kolmogorov-Smirnov test	

Fig. 5. Magnesium foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Gamma distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	-4145.318
Gamma[2]	-4126.263
Weibull[2]	-4114.508
[1]Subjected to Shapiro-Wilk normality test [2]Subjected to Kolmogorov-Smirnov test	

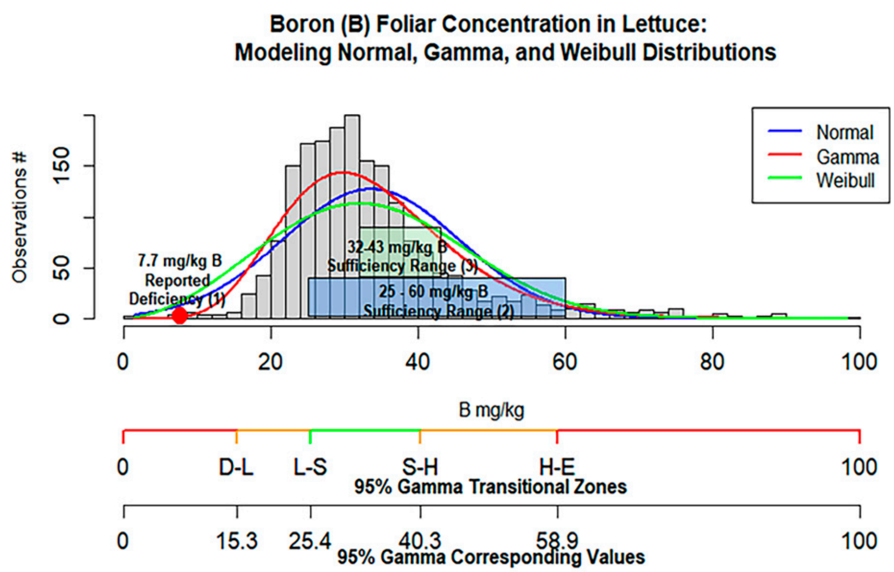
Fig. 6. Sulfur foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Gamma distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018) and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	20688.21
Gamma[2]	20005.83
Weibull[2]	20294.41

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

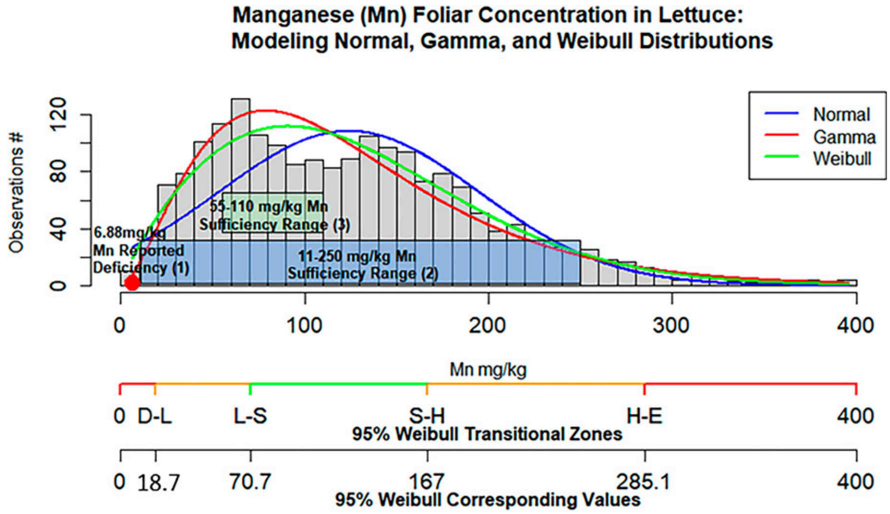
Fig. 7. Iron foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Gamma distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018) and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	15059.6
Gamma[2]	14640.01
Weibull[2]	15040.75

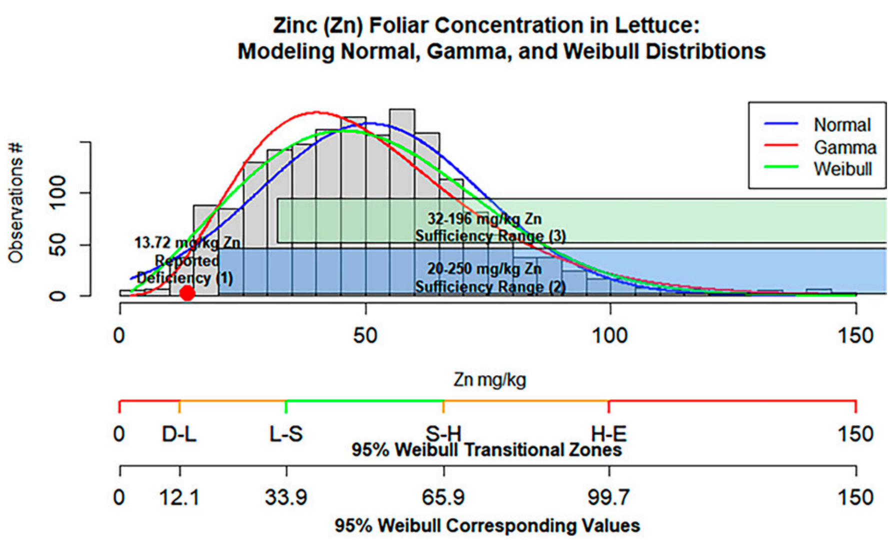
[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 8. Boron foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Gamma distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).



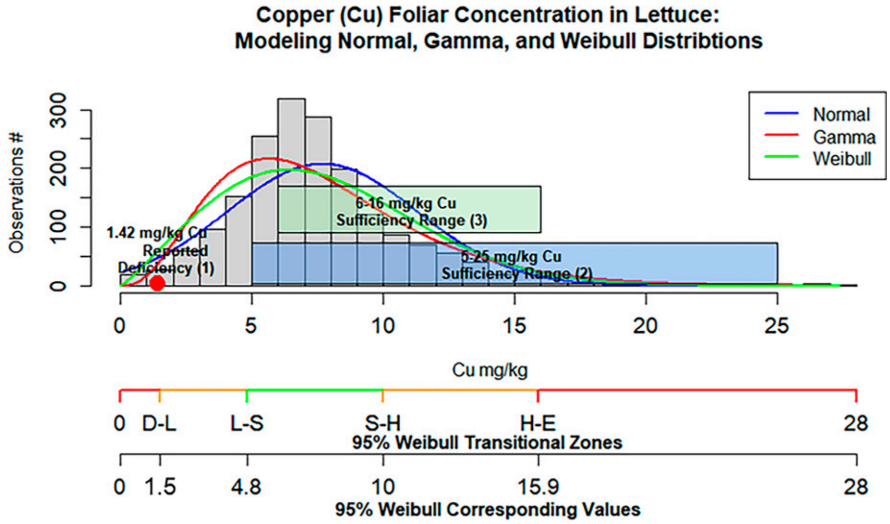
Distribution	BIC
Normal[1]	21841.89
Gamma[2]	21543.81
Weibull[2]	21521.52
[1]Subjected to Shapiro-Wilk normality test [2]Subjected to Kolmogorov-Smirnov test	

Fig. 9. Manganese foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	17364.95
Gamma[2]	17211.49
Weibull[2]	17227.73
[1]Subjected to Shapiro-Wilk normality test [2]Subjected to Kolmogorov-Smirnov test	

Fig. 10. Zinc foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).



Distribution	BIC
Normal[1]	10267.95
Gamma[2]	10223.01
Weibull[2]	10158.46

[1]Subjected to Shapiro-Wilk normality test
[2]Subjected to Kolmogorov-Smirnov test

Fig. 11. Copper foliar concentrations of lettuce modeled using Normal, Gamma, and Weibull distributions with interpretation ranges based on a Weibull distribution with four transitional points of deficient to low (D-L), low to sufficient (L-S), sufficient to high (S-H), and high to excessive (H-E), which correspond to 2.5%, 25%, 75%, and 97.5% of sample observations, respectively. Comparison ranges: (1) Henry et al. (2018), (2) Jones (2005), and (3) Bryson et al. (2014).

References Cited

Abbey M, Anderson NO, Yue C, Schermann M, Phelps N, Venturelli P, Vickers Z. 2019. Lettuce (*Lactuca sativa*) production in northern latitudinal aquaponic growing conditions. HortScience. 54(10):1757–1761. https://doi.org/10.21273/HORTSCI14088-19.

Beaufils ER. 1973. Diagnosis and recommendation integrated system (DRIS). Soil Sci. Bull. 1. Univ. of Natal, Pietermaritzburg, South Africa.

Bryson GM, Mills HA, Sasseville DN, Jones JB, Barker AV. 2014. Plant analysis handbook IV: A guide to sampling, preparation, analysis, and interpretation for agronomic and horticultural crops. Micro-Macro Publishing, Inc., Athens, GA, USA.

Caron J, Parent LE. 1989. Derivation and assessment of DRIS norms for greenhouse tomatoes. Can J Plant Sci. 69(3):1027–1035. https://doi.org/10.4141/cjps89-124.

Cera A, Montserrat-Martí G, Drenovsky RE, Ourry A, Brunel-Muguet S, Palacio S. 2022. Gypsum endemics accumulate excess nutrients in leaves as a potential constitutive strategy to grow in grazed extreme soils. Physiol Plant. 174(4):e13738. https://doi.org/10.1111/ppl.13738.

Eylands NJ. 2023. Anatomical, physiological, and photomorphogenic responses of lettuce and basil to far-red radiation under sole-source lighting. (PhD Diss). Michigan State University, East Lansing, MI, USA.

Fullmer FS. 1957. Leaf and soil analysis survey in two California potato growing areas. Proc Am Soc Hortic Sci. 70:385–390.

Gerovac JR, Craver JK, Boldt JK, Lopez RG. 2016. Light intensity and quality from sole-source light-emitting diodes impact growth, morphology, and nutrient content of Brassica microgreens. HortScience. 51(5):497–503. https://doi.org/10.21273/HORTSCI.51.5.497.

Gibson JL, Pitchay DS, Williams-Rhodes AL, Whipker BE, Nelson PV, Dole JM. 2007. Nutrient deficiencies in bedding plants. Ball Publishing, Batavia, IL, USA.

Guo W, Nazim H, Liang Z, Yang D. 2016. Magnesium deficiency in plants: An urgent problem. Crop J. 4(2):83–91. https://doi.org/10.1016/j.cj.2015.11.003.

Hall AD. 1905. The analysis of the soil by means of the plant. J Agric Sci. 1:65–88. https://doi.org/10.1017/S0021859600000162.

Handreck KA, Black ND. 2002. Growing media for ornamental plants and turf. UNSW Press, Sydney, Australia.

Henry JB, Cockson P, McCall I, Whipker BE. 2018. Comparing nutrient disorder symptomology of *Lactuca sativa* 'Salanova Green' and 'Salanova Red'. Acta Hortic. 1273:227–234. https://doi.org/10.17660/ActaHortic.2020.1273.31.

Henry JB, McCall I, Whipker BE. 2019. Nutrient disorders of *Lactuca sativa* 'Salanova Red'. Acta Hortic. 1266:283–290. https://doi.org/10.17660/ActaHortic.2019.1266.40.

Hoffer GN. 1926. Testing corn stalks chemically to aid in determining their plant food needs. Indiana Agr Exp St Bul. 298:1–31.

Jones JB Jr, Eck HV, Voss R. 1990. Plant analysis as an aid in fertilizing corn and grain sorghum. Soil Testing and Plant Analysis. 3:521–547. https://doi.org/10.2136/sssabookser3.3ed.c20.

Jones JB Jr. 2005. Hydroponics: A practical guide for the soilless grower. CRC Press, Boca Raton, FL, USA.

Krug BA, Whipker BE, McCall I, Cleveland B. 2010. Geranium leaf tissue nutrient sufficiency ranges by chronological age. J Plant Nutr. 33(3):339–350. https://doi.org/10.1080/01904160903470398.

Luo D, Wang W, Bai C, Zhu L, Li H, Zhou C, Qiu Q, Yao L. 2022. Foliar nutrient diagnosis norms for litchi (*Litchi chinensis* Sonn. cv. Feizixiao) in South China. J Plant Nutr. 45(20):3174–3187. https://doi.org/10.1080/01904167.2021.2021536.

Marschner H. 1995. Mineral nutrition of higher plants. 2nd ed. Academic Press, New York, NY, USA.

Matos GSBd, Fernandes AR, Wadt PGS, Pina AJA, Franzini VI, Ramos HMN. 2017. The use of DRIS for nutritional diagnosis in oil palm in the state of Pará. Revista Brasileira de Ciência do Solo. 41. https://doi.org/10.1590/18069657rbcs20150466.

Meng Q, Boldt J, Runkle ES. 2020. Blue radiation interacts with green radiation to influence growth and predominantly controls quality attributes of lettuce. J Am Soc Hortic Sci. 145(2):75–87. https://doi.org/10.21273/JASHS04759-19.

Mhango JK, Hartley W, Harris WE, Monaghan JM. 2021. Comparison of potato (*Solanum tuberosum* L.) tuber size distribution fitting methods and evaluation of the relationship between soil properties and estimated distribution parameters. J Agric Sci. 159(9-10):643–657. https://doi.org/10.1017/S0021859621000952.

Oliveira RC, da Silva JRR, Lana RMQ, de Azevedo Pereira AI, Castoldi R, de Camargo R, Luz JMQ. 2020. Fertilizer application levels in potato crops and the diagnosis and recommendation integrated system (DRIS). Agronomy. 11(1):51. https://doi.org/10.3390/agronomy11010051.

Owen WG. 2019a. Leaf tissue nutrient sufficiency ranges of four Heuchera cultivars by chronological age. HortScience. 54(10):1751–1756. https://doi.org/10.21273/HORTSCI14222-19.

Owen WG. 2019b. Hibiscus leaf tissue nutrient sufficiency ranges by chronological age. HortScience. 54(3):463–469. https://doi.org/10.21273/HORTSCI13482-18.

Owen WG. 2020. Establishment of leaf tissue nutrient sufficiency ranges of two Perovskia selections by chronological age. HortScience. 55(8):1303–1307. https://doi.org/10.21273/HORTSCI15124-20.

Papineau A, Krug BA. 2014. Osteospermum leaf tissue nutrient sufficiency ranges by chronological age. Acta Hortic. 1034:531–537. https://doi.org/10.17660/ActaHortic.2014.1034.67.

Partelli FL, Oliveira MG, Covre AM, Vieira HD, Machado Dias JR, Braun H. 2018. Nutritional standards and nutritional diagnosis of the Conilon coffee plants in phenological growth stages. J Plant Nutr. 41(19):2536–2546. https://doi.org/10.1080/01904167.2018.1510513.

Rao IM, Sharp RE, Boyer JS. 1987. Leaf magnesium alters photosynthetic response to low water potentials in sunflower. Plant Physiol. 84(4):1214–1219. https://doi.org/10.1104/pp.84.4.1214.

Reuter D, Robinson JB. 1997. Plant analysis: An interpretation manual. CSIRO Publishing, Melbourne, Australia. https://doi.org/10.1071/9780643101265.

Richards BN, Bevege DI. 1972. Principles and practice of foliar analysis as a basis for crop-logging in pine plantations: I. Basic considerations. Plant Soil. 36:109–119. https://doi.org/10.1007/BF01373461.

Scucuglia CL, Creste JE. 2014. Diagnosis and recommendation integrated system (DRIS) of tomato in greenhouse. Hortic Bras. 32:200–204.

Sema A, Maiti CS, Singh AK, Bendangsengla A. 2010. DRIS nutrient norms for pineapple on alfisols of India. J Plant Nutr. 33(9):1384–1399. https://doi.org/10.1080/01904167.2010.484286.

Slaton NA, Drescher GL, Parvej MR, Roberts TL. 2021. Dynamic critical potassium concentrations in soybean leaves and petioles for monitoring potassium nutrition. Agron J. 113(6):5472–5482. https://doi.org/10.1002/agj2.20819.

Soltanpour PN, Malakouti MJ, Ronaghi A. 1995. Comparison of diagnosis and recommendation integrated system and nutrient sufficiency range for corn. Soil Sci Soc Am J. 59(1):133–139. https://doi.org/10.2136/sssaj1995.03615995005900010021x.

Srivastava AK, Singh S. 2008. DRIS norms and their field validation in Nagpur mandarin. J Plant Nutr. 31(6):1091–1107. https://doi.org/10.1080/01904160802115359.

Ulrich A. 1948. Plant analysis – methods and interpretation of results, p 157–198. In: Kitchen HB (ed). Diagnostic techniques for soils and crops. American Potash Institute, Washington, DC, USA.

Ulrich A, Hills FJ. 1990. Plant analysis as an aid in fertilizing sugarbeet, p 429–447. In: Westerman RL (ed). Soil testing and plant analysis. 3rd ed. Soil Science Society of America, Madison, WI, USA.

Van Eysinga JR, Smilde KW. 1981. Nutritional disorders in glasshouse tomatoes, cucumbers and lettuce. Center for Agricultural Publications and Documents, Wageningen, Netherlands.

Veazie P, Pandey P, Young S, Ballance MS, Hicks K, Whipker B. 2022. Impact of macronutrient fertility on mineral uptake and growth of *Lactuca sativa* 'Salanova Green' in a hydroponic system. Horticulturae. 8(11):1075. https://doi.org/10.3390/horticulturae8111075.

Villaseñor D, Prado RM, Pereira da Silva G, Carrillo M, Durango W. 2020. DRIS norms and limiting nutrients in banana cultivation in the South of Ecuador. J Plant Nutr. 43(18):2785–2796. https://doi.org/10.1080/01904167.2020.1793183.

Weibull W. 1951. A statistical distribution function of wide applicability. J Appl Mech. 18(3):293–297. https://doi.org/10.1115/1.4010337.

Wickham H. 2011. ggplot2. Wiley Interdiscip Rev Comput Stat. 3(2):180–185. https://doi.org/10.18637/jss.v040.i01.