Accuracy, Precision, and Correlation to Yield Loss of Disease Severity Scales for Corky Root of Lettuce

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ABSTRACT

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A method for comparing disease severity scales using accuracy, precision, and correlation to yield loss was tested using disease assessment scales developed for corky root of lettuce. Two qualitative interval scales, a seven-level scale developed for assessing corky root severity of mature lettuce plants and a ten-level scale developed for screening seedlings for resistance 1 mo after inoculation, were compared with a 12-level Horsfall-Barratt (H-B) scale based on the percentage of the taproot area with corky root symptoms. To estimate accuracy and precision, six taproots in each of three severity classes (0–20, 20–80, and 80–100% of taproot showing corkiness) were rated by four plant pathologists who had experience assessing corky root disease, three general plant pathologists, and three novices using each of the scales. Estimates of accuracy and precision associated with each scale were made by calculating the bias and standard deviation, respectively, divided by a correction factor reflecting the number of intervals in each scale. Correlations between yield loss and severity score for each scale were compared using severity measurements from four corky root epidemics. No single scale was identified as the best for all situations. The qualitative scale for mature plants was generally the most accurate and most precise, but the H-B scale was most accurate for roots in the 20–80% severity class. Severity scores using the H-B scale correlated best with yield loss. The qualitative scale for seedlings was inferior to the other scales except for early season yield loss prediction. Novices assessed disease severity with equally high bias regardless of the scale used, whereas plant pathologists (with or without experience with corky root) were less biased when using two of the three scales. Correlations between disease severity and yield loss varied with lettuce phenological stage and severity scale used.

Corky root is an important disease of lettuce (*Lactuca sativa* L.) in the coastal areas of California, where much of the United States lettuce production is located (15). The causal agent is *Rhizomonas suberifaciens,* a recently described genus and species (21). The discovery of the causal agent has encouraged interest in the basic epidemiology of the disease.

One of the recommended first steps in the study of epidemics of new diseases is the development of reliable methods to estimate disease severity (1,8). Without reliable estimates, determination of disease progress rates, comparison of treatments such as cultivars or control measures, and prediction of future disease or yield loss is not possible (1,11,17).

Disease assessment scales often are used for disease severity measurements (7). There are two general types of disease assessment scales: qualitative scales based on a subjective division of disease severity into levels, and quantitative scales based on a quantitative trait, for example, percentage of the plant or plant part diseased (7,8,10,22). Ideally, scales should be quick, easy to use, applicable over a range of conditions, and reproducible, with sufficient intervals to represent all stages of disease development (1). Objective criteria such as accuracy, precision, and correlation to yield loss should guide selection of one scale over another, but these criteria have rarely been used (5,11). Lack of standardization of disease severity scales may preclude comparison among experiments and/or observers (22). With the research described here, we attempted to achieve standardization for assessment of corky root of lettuce.

Two qualitative disease severity scales have been used for corky root of lettuce (2,20). However, these scales have two drawbacks. First, although based on extensive experience, they are subjective, relying mostly on the originator's general concept of disease severity. Second, they measure disease qualitatively, accounting for depth of the cracks and girdling of the taproot as well as the percentage of taproot and lateral roots infected (2,20). Thus, they require nonparametric statistics for analysis.

To address these drawbacks, we constructed a disease severity scale based on one proposed by Horsfall and Barratt (6). Although widely used for aerial diseases, we could not find examples of such a scale for root diseases. In Horsfall-Barratt (H-B) scales, disease is expressed as a percentage of the plant area affected and divided into 12 levels, so that there are fewer levels around 50% infection. More levels near 0 and 100% reflect the increased visual acuity at low and high percentages according to the Weber-Fechner law (4,6) and compensate for the high variances typically encountered near 50% (6,10). The levels can be converted to percentages that approximate a continuous scale (8).

To illustrate an objective method for selection of a severity scale, we compared three severity scales for corky root disease of lettuce in California. This study reports results obtained from a comparison of accuracy and precision and from field experiments in which yield loss was correlated with corky root severity. A preliminary report has been published (13).

MATERIALS AND METHODS

Accuracy and precision. Accuracy and precision estimates for three severity scales were compared using a panel of 10 scoring participants and 18 lettuce roots. The lettuce roots were collected from several fields in Salinas, CA, that had been planted at different times with a susceptible cultivar, Salinas. The roots were selected for percent taproot surface showing corkiness such that six had less than 20%, six between 20 and 80%, and six greater than 80%.

The participants assessed disease severity using two qualitative scales and a quantitative H-B scale. Of the qualitative scales, one had seven levels (0–6) and was developed for assessing corky root severity of mature lettuce plants. Based on photographs illustrating each level of severity, the levels reflected coverage of the taproot and laterals by corkiness (20). A pinched taproot was the most severe level (19). This scale will be referred to as the "mature-plant scale." The second qualitative scale had 10 levels (0–9) and was developed for screening seedlings for resistance to corky root 30 days after inoculation. Line drawings were used to illustrate each level according to degree of yellowing, corkiness, and depth of fissures on the taproot, and degree of wilting and decline of the shoot (2). This scale will be referred to as the "seedling scale." The H-B scale had 12 levels (1 = 0%, 2 = 0–3%, 3 = 3–6%, 4 = 6–12%, 5 = 12–25%, 6 = 25–50%, 7 = 50–75%, 8 = 75–87%, 9 = 87–94%, 10 = 94–97%, 11 = 97–100%, 12 = 100%) (6) and was developed from photographs of diseased roots. The actual percentage of surface area of the taproot that showed

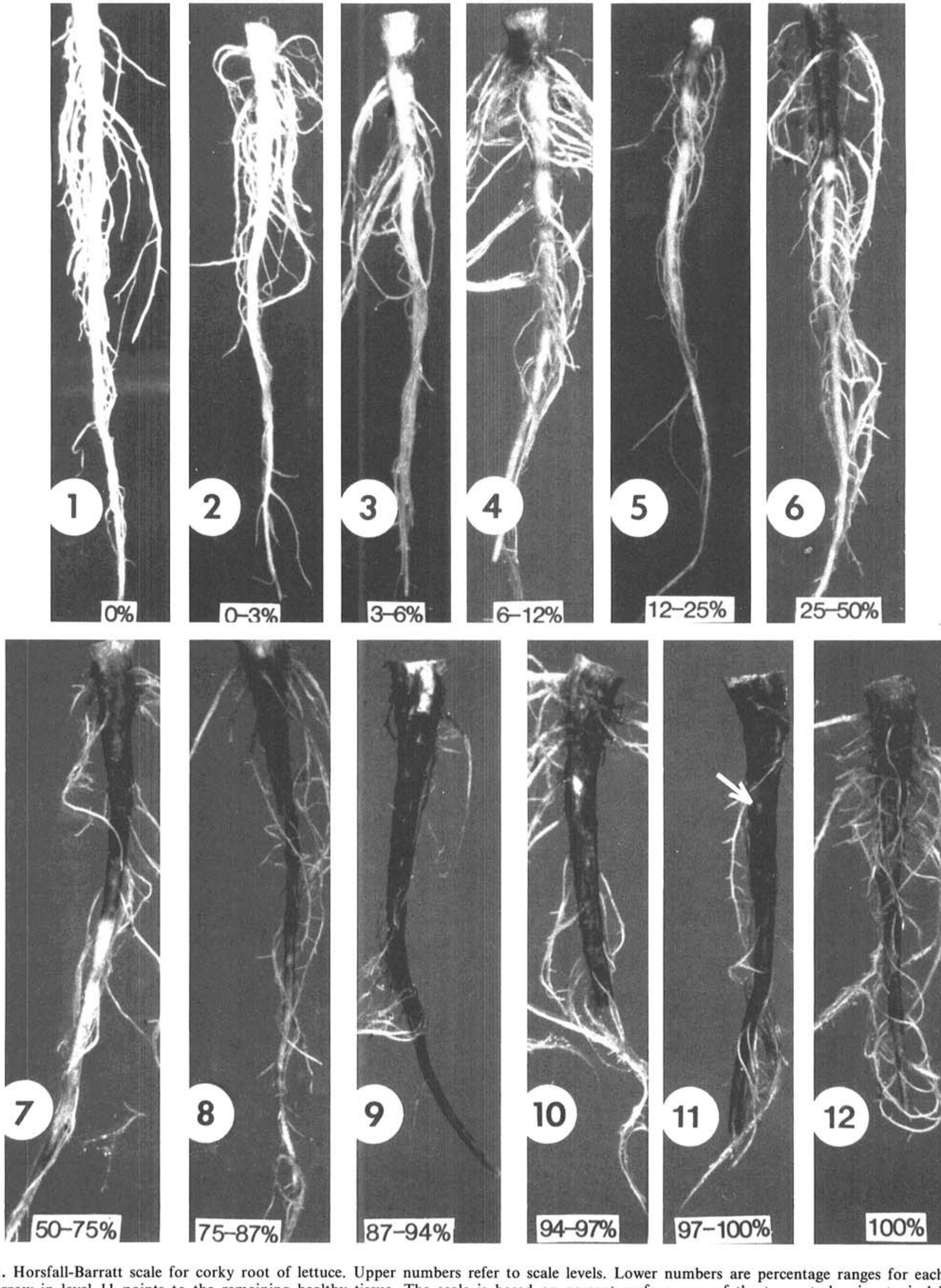

Fig. 1. Horsfall-Barratt scale for corky root of lettuce. Upper numbers refer to scale levels. Lower numbers are percentage ranges for each level. The arrow in level 11 points to the remaining healthy tissue. The scale is based on percent surface area of the taproot showing typical brown, corky discoloration.

brown, corky discoloration typical of the disease was determined by the ratio of diseased to healthy areas. This ratio was calculated from the weights of diseased and healthy areas on photocopies of approximately 100 roots. A typical root photograph representing each severity level was included in the scale (Fig. 1).

The participants were divided into three groups based on expertise in assessing plant disease. Three people were novices without experience in plant disease assessment. Three people were plant pathologists, unfamiliar with corky root, but experienced in disease assessment. The other four people had extensive experience with corky root, and three of them were originators of the mature-plant, seedling, and H-B scales, namely A. H. C. van Bruggen, P. R. Brown, and R. D. O'Brien, respectively.

All 10 people assessed disease severity on each root using each of the scales. Disease assessment was done in stages to approximate complete randomization and minimize confounding effects such as scale and participant group. A set of six roots with wide ranging levels of corky root and one severity scale composed a station. Each person went to each station in turn and assessed disease severity on all six roots. New stations were constructed by moving the severity scales to a new set of roots and starting people at different stations at the beginning of each rotation. Participants using the H-B scale were instructed to assess the level (1–12) directly without converting from percentages.

An estimate of accuracy was made by determining bias, calculated as the absolute value of the difference between recorded scores and the "correct" score. The absolute value was used because we were interested in the magnitude of the bias only, not its direction. Scores for each root and scale recorded by the originator of each scale were considered "correct," because unbiased scores for qualitative scales could not be obtained empirically. Unbiased scores could be obtained for the H-B scale (10), but bias was calculated using the "correct" score of the originator of this scale to allow comparison with the measures of bias for the qualitative scales. Because the bias calculated in this way would be zero for scores obtained from the originators of the scales, bias for scores by the originators were omitted from the statistical analysis. The bias was standardized by division by the number of intervals in each scale (six, nine, and 11 for the mature-plant, seedling, and H-B scales, respectively). This correction factor represents the maximal bias; therefore, the standardized bias is equivalent to a proportion of the maximal bias and is equal to 1 minus the accuracy. The standardized bias was analyzed as a $3 \times 3 \times 3$ factorial design with three scales, three groups of participants, and three root classes. There were six roots per class and three participants per group.

A measure of the precision associated with each scale was made by calculating the variability among the participants for each scale and root. The standard deviation for each scale and each of the 18 roots was divided by the correction factor described above, resulting in a scaled measure of variability (1 minus precision). The standardized variability was analyzed as a 3×3 factorial design with three scales and three root classes. There were six roots per class.

Correlation of disease severity and yield loss. Correlations between disease severity and yield loss were determined for all three scales in a field experiment at Davis, CA. Approximately 10 wk before planting, the soil was fumigated with 500 kg/ha methyl bromide + chloropicrin (53:47, v/v) to reduce populations of *R. suberifaciens* possibly remaining from previous experiments. Twenty microplots (1×2 m) enclosed by 50-cm-deep fiberglass rings (20) were seeded with iceberg lettuce cultivar Salinas in two rows, 50 cm apart, on each microplot bed. Immediately after seeding, half of the plots were sprinkled with a broth culture of *R. suberifaciens* strain CA1 (20) at 5×10^8 cfu/m^2. Bacterial concentration was estimated by dilution plating on S medium (20). The other plots received distilled water. Plots were arranged in a completely randomized design with five replications of two microplots per treatment. The experiment was performed four times: in the spring of 1989 and 1990 and in the fall of 1988 and 1989. Standard fertilization, irrigation, and pest control methods were used (20).

Five plants per replication were uprooted approximately weekly starting 7–20 days after planting. The sampling pattern was systematic and used the space efficiently while minimizing unwanted plant competition effects and approximating commercial thinning and spacing practices. Each plant was scored for phenological growth stage and disease severity by the first author, using all three corky root scales. A phenological scale was developed after a literature survey failed to yield a suitable scale for development of iceberg lettuce. Lettuce growth was divided into 14 different phenological stages (Fig. 2) based on the number of true leaves per plant (stages 1–8, corresponding to the first eight true leaves), similarity to illustrative photographs when plants were in the rosette stage (stages 9–10), and appearance, feel, and density of the head (stages 11–14). By using disease severity scores at similar developmental stages, the results from all four seasons could be combined.

Shoot fresh weight is most strongly affected by corky root (12,14), and fresh weights of the last two harvests, 1 wk apart, were used to determine yield loss. Yield loss caused by corky root was calculated as 1 minus the ratio of the weight of shoots from each infested replication and the mean weight of shoots from healthy plots.

Statistical analysis. Statistical computations were made using software from Statistical Analysis Systems (16). The SAS general linear models procedure was used to perform analysis of variance on standardized bias and variability values. Residual values were checked for normality with the Shapiro-Wilk statistic (16). Selected hypotheses were tested with linear contrasts, and contrast estimates were calculated with the estimate statement (16).

Disease scores obtained with the qualitative mature-plant and seedling scales were ordinal data and would require nonparametric statistical analysis. To calculate correlations with yield loss, Spearman rank correlations on a per plant basis would be appropriate. However, the experimental unit for yield loss assessment was a plot rather than a plant, and Spearman rank correlations between disease scores and yield loss per plant could not be determined. Thus, Pearson product moment correlation coefficients (16) were calculated between yield loss and mean disease severity score per plot for each scale at each phenological stage. H-B scores were first converted to percentages using the arithmetic means of the class limits. Scores of the mature-plant and seedling scales were used directly, ignoring the ordinal nature of the data. Plots of yield loss vs. disease severity were examined to ensure that correlations were linear.

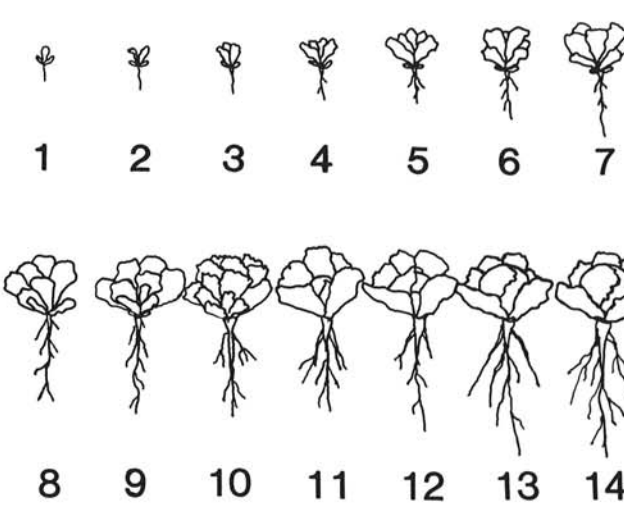

Fig. 2. Phenological stages for development of iceberg lettuce. Stages 1–8 are based on number of true leaves, stages 9 and 10 on rosette formation, and stages 11–14 on head formation. At stage 13 the head is still soft (density < 0.43 gcm^{-3}) and at stage 14 the head is mature (density > 0.43 gcm^{-3}).

RESULTS

Bias. Standardized bias was significantly affected by corky root severity class (< 20, 20–80, and > 80%) and severity scale, but not by participant group (Table 1). The interactions between severity class and scale, and between participant group and scale, were significant. Bias ranged from 0.062 to 0.218 (Table 2).

Contrast analyses to unravel the significant interaction between participant group and scale (Table 1) showed that general plant pathologists and those experienced with corky root assessed disease severity with less bias when using the mature-plant and H-B scales than when using the seedling scale, whereas novices assessed disease severity with equally high bias regardless of the scale they used ($P < 0.01$; Table 2). The difference in bias between the mature-plant and H-B scales vs. the seedling scale was larger for plant pathologists experienced with corky root than for general plant pathologists ($P = 0.01$). The hypothesis that novices would be less biased with a simple scale (mature-plant scale) than with more complex scales, whereas plant pathologists (with or without experience with corky root) would be equally biased with all scales, was rejected ($P > 0.05$). The hypothesis that disease assessments made by novices with the H-B scale would be more biased than those made with the mature-plant scale, while disease assessments made by general plant pathologists and those experienced with corky root would be equally biased with these scales, was rejected as well ($P > 0.05$).

Contrast analyses to examine the significant interaction between corky root severity class and scale (Table 1) indicated that scores made with the mature-plant scale for roots in the highest severity class were less biased than scores made with the seedling and H-B scales ($P < 0.01$; Table 2). Moreover, the H-B scale resulted in less bias for the middle range of severity classes, but not for the extreme severity classes ($P = 0.01$), compared with the other scales. The seedling scale was much less biased at low disease severities (< 20%) than at medium and high disease severities, while the difference in bias among disease severity classes was less pronounced with the other two scales ($P < 0.01$). On average, roots in the middle range of severity classes were scored with more bias than roots in the extreme ranges ($P < 0.01$), and roots in the lowest severity range were scored with less bias than roots in the highest severity range ($P < 0.01$).

Contrast analyses to examine the main effects of corky root severity class (Table 1) on bias showed that across participants, corky root severity scores had the highest bias with the seedling scale and the lowest bias with the mature-plant scale ($P < 0.01$). Scores with the H-B scale were less biased than those with the qualitative scales ($P < 0.01$), but this was primarily due to the high bias with the seedling scale compared with the mature-plant and H-B scales ($P < 0.01$).

Precision estimates. There were significant effects of corky root severity class and scale on the standardized variability but no significant interactions (Table 1). The H-B scale did not result in less variability than the other scales (Table 3). The simplest scale, the mature-plant scale, however, resulted in less variability than the more complex scales.

Roots with less than 20% and more than 80% of their surface area showing corkiness were scored more precisely than roots with 20–80%. Scores of roots with less than 20% were rated more precisely than roots with greater than 80% severity.

Correlations between yield loss and corky root severity. Yield loss in the different field experiments ranged from 11 to 89%, with the highest losses in the fall crops (data not shown). All correlations between yield loss and disease severity were significant at $P = 0.025$ for each phenological stage (Table 4). The seedling scale and H-B scale had the highest correlation at the early rosette stage ($r = 0.91$ and 0.92, respectively), while the mature-plant scale had the highest correlation at heading ($r = 0.84$). Scores obtained with the mature-plant and H-B scales maintained high correlations with yield loss throughout all phenological stages. Correlations between yield loss and corky root severity assessed with the seedling scale were low at more advanced stages. For plants younger than the seven leaves stage, disease severities assessed with any of the scales were too low to calculate correlations. The mature-plant scale would not be useful even at the seven leaves stage because all scores were zero. For all scales, the highest correlation between disease severity and yield loss was obtained when there was a wide range of disease severity scores.

TABLE 1. Summary analysis of variance of standardized bias and variability values associated with corky root severity scores[a] recorded by nine or 10 participants using three assessment scales (qualitative scales for mature plants and for seedlings and a quantitative Horsfall-Barratt scale)

	Bias[b]		Variability[c]	
Source of variation	df[d]	MS[e]	df	MS
Root severity class	2	0.19***[f]	2	0.016**
Severity scale	2	0.46***	2	0.033***
Participant group	2	0.01	···	···
Root class × scale	4	0.06***	4	0.002
Group × scale	4	0.05***	···	···
Group × root class	4	0.02	···	···
Error	466	0.007	45	0.003

[a] The roots were divided into three severity classes: <20, 20–80, and >80% of the surface area of the taproot showing corkiness.
[b] Bias = deviation from "correct" score/number of intervals in the scale. Bias was determined for 18 roots by three participant groups (three general plant pathologists, three plant pathologists experienced with corky root, and three novices) using three severity scales.
[c] Variability = standard deviation/number of intervals in the scale. The standard deviations for each of 18 roots were calculated using scores recorded by 10 participants using three severity scales.
[d] Degrees of freedom.
[e] Mean squares.
[f] Significance levels: *** $P = 0.01$; ** $P = 0.01$.

TABLE 2. Bias associated with corky root disease severity scores recorded by three groups of participants using a seven-level, qualitative scale for mature plants; a ten-level, qualitative scale for seedlings; and a Horsfall-Barratt (H-B) twelve-level, quantitative scale

	Mean bias[a]					
	Participants[b]			Severity class[c]		
Treatment	Corky root experts	General plant pathologists	Novices	<20%	20–80%	>80%
Mature-plant scale	0.071	0.084	0.109	0.065	0.137	0.062
Seedling scale	0.218	0.169	0.159	0.111	0.216	0.218
H-B scale	0.072	0.087	0.120	0.069	0.099	0.111
Corky root experts				0.098	0.156	0.138
General plant pathologists				0.076	0.131	0.155
Novices				0.092	0.193	0.132
Standard error 0.098						

[a] Bias was calculated from corky root severity scores recorded by three participant groups using each of the three scales. Each person scored 18 roots divided into three severity classes. Bias = deviation from "correct score"/number of intervals in the scale.
[b] Corky root experts had extensive experience with corky root, general plant pathologists had experience with other diseases, and novices had no experience with plant diseases.
[c] Three disease severity classes, based on percent taproot covered with corkiness, contained six roots each.

DISCUSSION

Results from this study indicate that objective criteria, such as accuracy, precision, and correlation with yield loss, can be used to compare disease severity scales. The scales tested were diverse with respect to simplicity (number of levels), realism (photographs vs. drawings), intended use (seedlings vs. mature plants), choice of levels (objective vs. subjective), and statistical restrictions (qualitative vs. quantitative).

No single scale was identified as the best for all situations. The simplest scale, the qualitative scale for mature plants, was the most accurate and most precise scale. Another advantage of this scale was the relatively short time needed for disease assessment. The H-B scale also was very accurate but somewhat less precise than the mature-plant scale. This scale had the advantage of statistical simplicity because it is quantitative and does not require nonparametric statistics for analysis. The qualitative scale for seedlings was inferior to the other scales with respect to accuracy and precision. The results on accuracy must be viewed with caution, however, since the bias measurements were based on the ability of the designer of each scale to illustrate his or her individual concept of disease severity. Moreover, the number of plant samples and scoring scales was limited. Thus, no generalized conclusion about bias or precision associated with each type of scale (qualitative or quantitative) could be made.

The scales were most useful for predicting yield loss at phenological stages when disease severities fell within moderate ranges and when the range of disease severities was widest. Prediction of yield loss when plants were still young (and severities were low) were subject to more uncertainty, probably in part because environmental conditions could fluctuate widely between disease assessment and harvest. Severity scores using the H-B and seedling scales were correlated with yield loss starting at the seven leaves stage, with the highest correlation at the early rosette stage of lettuce growth. Severity scores made with the mature-plant scale were not correlated with yield loss before the rosette stage. This was probably due to the limited number of levels of this scale. Hau et al (4) showed that the accuracy of a scale is dependent on the number of levels when the frequency distribution of disease severities is skewed to low severity values. Disease assessment near lettuce maturity (when severities were high) was a poor predictor of yield loss when the seedling or H-B scale was used. The reason was probably that severity scores had approached the highest possible level (R. D. O'Brien, *unpublished*) and the scales were unable to document further symptom development. The qualitative scale developed for mature plants was most effective at this time, since its highest score takes into account that taproots can be pinched off in addition to being 100% infected. The dependence of prediction of yield loss on phenological stage and choice of disease assessment scale illustrates the importance of comparing various disease severity scales at different phenological stages to develop critical or multiple point models for yield loss (8,11).

In this study, we did not measure the intrascorer variability, only the interscorer variability. The intrascorer variability, the variability among scores for one plant by the same person, has rarely been determined (4). The interscorer variability, the person-to-person variability for scores for one plant, has been studied more often. Several authors reported increased interscorer variability in disease assessment between 25 and 75% disease severity (3,4). This variability may be partly due to the ability of each person to better distinguish between disease severities at extreme disease levels. The dependence of the ability to

TABLE 3. Standardized variability[a] associated with 10 people who recorded corky root disease severity scores for 18 roots, divided into three severity classes (based on percentage of the root surface area showing corkiness) using three disease severity scales

Severity scale and class	Standardized variability	Contrast hypotheses	Contrast estimates
Corky root severity scale			
Mature-plant scale (seven-level, qualitative)	0.052[b]	Qualitative scales vs. Horsfall-Barratt scale	−0.024
Seedling scale (ten-level, qualitative)	0.131	Mature-plant vs. seedling scale	−0.079***[c]
Horsfall-Barratt scale (12-level, quantitative)	0.115	Sevel-level scale vs. 10- and 12-level scales	0.071***
		10- vs. 12-level scale	0.016
Corky root severity class			
0–20% corkiness	0.067[d]	(0–20%) and (80–100%) vs. (20–80%)	0.038*
20–80% corkiness	0.125	(0–20%) vs. (80–100%)	−0.040*
80–100% corkiness	0.107		
Standard error	0.057		

[a] Standardized variability = standard deviation/number of intervals in the scale.
[b] Mean of 18 roots scored by 10 people.
[c] Significance levels: * $P = 0.05$; *** $P = 0.0001$.
[d] Mean of six roots scored by 10 people using three severity scales.

TABLE 4. Correlations of lettuce yield loss[a] caused by corky root and disease severity[b] at seven phenological lettuce growth stages using three severity scales[c]

		Linear correlation			Disease score range		
Phenological stage	Stage number	Mature-plant scale (0–6)	Seedling scale (0–9)	H-B scale (1–12)	Mature-plant scale (0–6)	Seedling scale (0–9)	H-B scale (1–12)
Seven leaves	7	NC[d]	0.78[e]	0.70	0	1–5	1–6
Early rosette	9	0.70	0.91	0.92	0–4	3–8	2–11
Late rosette	10	0.82	0.77	0.85	0–5	4–9	4–11
Heading	12	0.84	0.67	0.78	1–6	6–9	5–12
First harvest	13	0.78	0.47	0.76	2–6	7–9	7–12
Final harvest	14	0.83	0.49	0.77	3–6	7–9	7–12

[a] Shoot fresh weight losses were calculated as 1 − (weight of shoots from infested plots)/(mean weight of shoots from noninfested plots) and were the means of five plants per plot from two harvests, 1 wk apart, when lettuce heads were mature. There were five replications in each of two spring crops (1989 and 1990) and two fall crops (1988 and 1989).
[b] Disease severity scores were the means of five roots per plot for each growth stage. There were five replications in each of two spring crops (1989 and 1990) and two fall crops (1988 and 1989).
[c] The mature-plant and seedling scales were qualitative scales developed for mature plants (range = 0–6) and seedlings (range = 0–9), respectively. The H-B scale was a Horsfall-Barratt quantitative scale (range = 1–12), converted to percentage of root surface area showing corkiness.
[d] Not calculated.
[e] Values >0.44 are significant at $P = 0.025$.

distinguish between severities on disease level could be described by the Weber-Fechner law according to Horsfall and Barratt (6) and some other researchers (1,9), but not according to others (3–5,17). In our study, scores for roots in the moderate severity class (20–80% of the root showing corkiness) were scored less accurately and less precisely than roots in the extreme classes (Tables 2 and 3). Individual scorers assessed roots in the intermediate disease severity class with more accuracy (i.e., less bias) with the H-B scale than with the other scales. However, the bias was still higher for the 20–80% class than for the 0–20% disease severity class, despite the correction for less accuracy at intermediate disease severities with the H-B scale. The precision of disease assessment for roots in the 20–80% severity class was not improved with the H-B scale when compared with the other scales (no significant scale × class interaction). Thus, only part of the high variability at moderate disease severities could possibly be explained by the Weber-Fechner law.

The number of participants and lettuce roots was fairly small, and participants could possibly have recognized individual taproots. Thus, we have to be cautious drawing conclusions about the different participant groups. Nevertheless, general plant pathologists and those experienced with corky root seemed to score more accurately with two of the three scales than novices. One of these scales was the H-B scale, which probably requires more training than was given to the novices. Although we hypothesized that novices would use the simplest scale with the least bias, this was not the case. Variability in ability to accurately assess disease has been reported (1,4), and people can be trained to improve their accuracy (18). Methods that eliminate the effect of human assessment, such as video image analysis (10), can be used for certain diseases. However, since this technology requires fairly uniform surfaces and clear distinctions between diseased and nondiseased areas based on black and white contrast (10), video image analysis may have limited potential for diseases such as corky root of lettuce. Moreover, symptoms of other diseases could not be easily distinguished from those of corky root with video image analysis based on grey scales (19). Color-based video image analysis might overcome some of these drawbacks.

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