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Standard Area Diagrams for Aiding Severity Estimation: Scientometrics, Pathosystems, and Methodological Trends in the Last 25 Years

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ABSTRACT

Standard area diagrams (SAD) have long been used as a tool to aid the estimation of plant disease severity, an essential variable in phytopathometry. Formal validation of SAD was not considered prior to the early 1990s, when considerable effort began to be invested developing SAD and assessing their value for improving accuracy of estimates of disease severity in many pathosystems. Peer-reviewed literature post-1990 was identified, selected, and cataloged in bibliographic software for further scrutiny and extraction of scientometric, pathosystem-related, and methodological-related data. In total, 105 studies (127 SAD) were found and authored by 327 researchers from 10 countries, mainly from Brazil. The six most prolific authors published at least seven studies. The scientific impact of a SAD article, based on annual citations after publication year, was affected by disease significance, the journal's impact factor, and methodological innovation. The reviewed SAD encompassed 48 crops and 103 unique diseases across a range of plant organs. Severity was quantified largely by image analysis software such as QUANT, APS-Assess, or a LI-COR leaf area meter. The most typical SAD comprised five to eight black-and-white drawings of leaf diagrams, with severity increasing nonlinearly. However, there was a trend toward using true-color photographs or stylized representations in a range of color combinations and more linear (equally spaced) increments of severity. A two-step SAD validation approach was used in 78 of 105 studies for which linear regression was the preferred method but a trend toward using Lin's correlation concordance analysis and hypothesis tests to detect the effect of SAD on accuracy was apparent. Reliability measures, when obtained, mainly considered variation among rather than within raters. The implications of the findings and knowledge gaps are discussed. A list of best practices for designing and implementing SAD and a website called SADBank for hosting SAD research data are proposed.

Quantification of disease is a requirement for research in phytopathology and is needed for practical disease management (Gaunt 1995a,b). The quantity of disease or disease intensity can be summarized by prevalence, incidence, and severity (Bock et al. 2016; Nutter et al. 1991). For a diseased sampling unit (e.g., leaf), disease severity (the focus of this study) describes the proportion or percentage of total host area affected by the disease and is generally expressed as an average of the severity across all units (Madden et al. 2007). Severity can be estimated visually or measured using image analysis, canopy reflectance, or molecular or immunological methods (Bock et al. 2010). Despite the advances in image-based software and tools available to assist in automatic or semiautomatic disease measurement (Barbedo 2014; Lamari 2002; Pethybridge and Nelson 2015), qualitative or quantitative visual estimates remain the most commonly used method for severity assessment in both controlled-environment studies and in the field.

Difficulties associated with visual estimates of disease severity on plant specimens have been well documented and methods have been developed to improve accuracy (closeness to the actual value) (Nutter et al. 1991). The context and importance of accuracy in plant disease assessment was addressed recently (Bock et al. 2016). The variability and biases of the estimates (inaccuracy) for a specimen can have ramifications for the data and subsequent analysis and, consequently, the conclusions or recommendations that stem from the research (Chiang et al. 2016; Parker et al. 1995). By definition, consistently accurate estimates must have high precision (closeness of repeat estimates to one another). However, highly precise estimates are not necessarily accurate (Bock et al. 2016; Nita et al. 2003; Nutter et al. 1993). Reliability measures do not consider actual severity values but are also important to depict the similarity within estimates or measurements obtained by the same rater (intrarater reliability, or repeatability) or by different raters or methods (interrater reliability, or reproducibility) (Madden et al. 2007; Nutter et al. 1993).

Proposals have been made to improve accuracy and reliability of visual severity estimates by using disease diagrams as a standard reference template prior to or during the assessments (Cobb 1892; James 1971; James et al. 1968), or by training raters using computer-generated images (Nutter and Schultz 1995). Standard area diagrams (SAD) are defined as a set of illustrations depicting incremental percent severity values (Nutter et al. 1993) but the name "diagrammatic scale" is also commonly used in the literature (Amorim et al. 1993; Godoy et al. 1997). The SAD are designed to aid raters to accurately interpolate the percent severity between the guide reference pair most closely resembling the specimen in question (James 1971).

SAD have a long history in plant pathology dating back to the late 1800s, when the Cobb scale was developed with five diagrams illustrating a range of severities of rust pustules on wheat leaves (Cobb 1892). Subsequently, SAD have comprised a series of illustrations of incremental and known disease severity with patterns similar to actual symptoms, and have been developed for many diseases (Bock et al. 2010; Campbell and Madden 1990; Dixon and Doodson 1971; James 1971, 1974). General guidelines for preparing a SAD were outlined in the early literature (Berger 1980; James 1971; Large 1966) and have guided researchers who have incorporated advances in image analysis to measure actual severity and to prepare diagrams (Bock et al. 2010).

It was only during the last 20 years that the importance of testing SAD for improvements in accuracy, precision, and reliability was

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acknowledged—a process commonly referred to as validation. For validation, actual severity values are required and a range of statistical methods (e.g., linear regression, concordance analysis, and so on) has been used to evaluate accuracy and precision of estimates, as well as sources and magnitudes of error of the estimates (Bock et al. 2010; Madden et al. 2007). In general, aided estimates are usually more reliable, precise, and accurate when compared with unaided estimates but error may persist due to factors related to the disease (symptomatic patterns) and raters' intrinsic ability or experience (Braido et al. 2014b; Debona et al. 2015; Duan et al. 2015; González-Domínguez et al. 2014; Yadav et al. 2013).

Four phases in the evolution of SAD can be described: phase I, a presumptive phase, when SAD were assumed to help and validation was not considered (James 1971, 1974; James et al. 1968; Large 1966); phase II, a period when the use of SAD was demonstrated to provide estimates close to the true values, yet not taking unaided estimates into account (Amorim et al. 1993; Godoy et al. 1997; Michereff et al. 1998); phase III, a period beginning in the early 2000s, when both unaided or aided and actual estimates were used and P values of null hypothesis significance tests (NHST) for the departures of the slope and intercept of the linear model from 1 and 0, respectively, were considered to indirectly assess the improvement in accuracy (Michereff et al. 2000); and phase IV, the current period, when concordance analysis began to substitute for linear regression in SAD research (Spolti et al. 2011), and the effect of the SAD on the accuracy components are tested, formally comparing unaided and aided estimates by a sample of raters (Yadav et al. 2013).

This systematic review is focused on SAD studies beginning with phase II (the early 1990s), when 39 SAD for different plant diseases were cataloged in a sentinel chapter on disease assessment (Campbell and Madden 1990). Since the early 1990s, the number of SAD developed by research groups from several countries working solely or collaboratively has proliferated (Bock et al. 2010), and an updated review of the field is pertinent to establish the current state of knowledge, reveal scientific network collaborations, summarize methodological trends, and discuss further priorities for research. Previously, a range of methods to measure and estimate disease severity was thoroughly reviewed but only a relatively small section was dedicated to SAD (Bock et al. 2010; Madden et al. 2007). Hence, the objectives of this article were to (i) review post-1990 literature by applying defined criteria to search and select peer-reviewed research articles reporting SAD development or validation; (ii) summarize publication metrics; and (iii) scrutinize full texts to extract, summarize, and detect methodological trends.

TABLE 1. Group, name, and description of variables extracted from peer-reviewed articles reporting the development or validation of standard area diagrams (SAD) for aiding visual estimation of plant disease severity[a]

Variable group and description	Example
Publication	
First author name	Godoy et al.
Number of authors	3
Country of the research group	Brazil
Publication type	Article
Publication year	2006
Journal name	Trop. Plant Pathol. (Fitopatol. Bras.)
Language of publication	EN
Number of citations in Google Scholar	164
Crop and pathogen	
Crop name	Soybean
Depicted organ	Leaf
Disease name	Asian Soybean rust
Pathogen binomials	*Phakopsora pachyrhizi*
Pathogen group	Fungi
SAD in the study	1
Number of sampled specimens	NA
SAD development	
Image acquisition	Digital
Actual severity quantification method	Scion Image
Diagram type	Drawing
Diagram color scheme	Black-white
Number of sets	1
Number of illustrations in the set	6
H-B as a basis for increments in severity[b]	Yes
Minimum severity	0.6
Maximum severity	78.5
SAD validation	
Validation scheme	Unaided and aided
Number of aided assessments	1
Number of raters	8
Number of experienced raters	0
Number of specimens assessed	44
Statistics of repeatability	No
Statistics of reproducibility	No
Statistics of accuracy	Linear regression
Accuracy coefficients	R^2, intercept, and slope

[a] One example is provided for the most-cited article published within the 1991 to 2017 period (Godoy et al. 2006).

[b] H-B = Horsfall-Barratt scale (based on the nonexistent Weber-Fechner law of visual acuity).

MATERIALS AND METHODS

Sources of SAD articles. A systematic review of peer-reviewed articles (hereafter referred to as a "study") reporting the development of SAD was conducted in bibliographic databases. We did not include SAD published in sources other than peer-reviewed literature such as books, booklets, extension articles, fact-sheets, and websites. The search was limited to articles since the year of publication of the chapter on disease assessment (Campbell and Madden 1990). First, a search was conducted using the "Advanced Search" tab of the Web of Science (http://apps.webofknowledge.com) using the following syntax in the article title: TI=("diagrammatic scale" or "standard area diagram" or "diagrammatic scales" or "standard area diagrams"). The publication period was restricted to the period from 1991 to 2016. Second, we expanded our search to Google Scholar (https://scholar.google.com.br) using the same keywords in the title (example of syntax used: allintitle: "standard area diagram"). Third, we included an additional keyword phrase for the name of the diagrammatic scale in Portuguese and Spanish ("escala diagramática"), because many articles were published in these two languages in national journals. Studies found in Google Scholar that were not found in the Web of Science search, after the duplicates were removed manually, were included. Finally, a few additional studies not found in the two search engines were selected after scrutinizing the literature cited in the previously selected studies.

The titles and abstracts of the studies retrieved in the search were inspected and those not dealing with plant disease assessment or not specifically detailing development and validation of the new SAD were excluded. The full texts of the studies were inspected and those that did not match the following criteria were excluded: (i) the plant diseases and causal agents should be clearly defined; (ii) the development of the SAD should be fully described; and (iii) the SAD was illustrated, with each diagram of the set depicting a specified percent severity.

Study and SAD-related variables. From each eligible study, 34 variables were extracted from the text, tables, and figures after a careful examination of the full-text articles. Four broad groups of variables were defined as follows: (i) publication characteristics; (ii) plant, disease, and pathogen name and characteristics; (iii) SAD development methods; and (iv) SAD validation methods (Table 1). A subset of key variables from each group was selected and presented for each SAD. Descriptive statistics (proportion, mean, minimum, and maximum) summarized some variables, and Pearson's correlation and linear regression analysis were used to summarize these data and quantify associations or functional relationships between some variables or between variables and time. First- and second-order (quadratic) regression models were fitted to determine the relationship of severities depicted in a SAD in order to evaluate whether an approximate linear or nonlinear (Horsfall-Barratt [H-B] scale or Weber-Fechner law used as the rationale) incremental scale was used as a basis to set the intervals between severities. All of these analyses were performed in the R statistical computing environment (R Core Team 2013).

Authoring frequency and coauthorship network analyses. The selected articles were organized using bibliographic manager software (Mendeley Desktop v. 1.17.6 for Mac). The names of the authors were inspected after import of the PDF files, checked for possible double entries due to misspelling, and standardized for format. From Mendeley, data were exported as a XML file, which was imported into R for further data-processing and text-mining analyses. Two main analyses were conducted: (i) summary of the total number of authors, number of unique authors, number of authors per study, and frequency of studies per unique author, the latter depicted as a word cloud; and (ii) a coauthorship network analysis was performed to depict collaboration trends and social structure by identifying leading scientists and their connection to others in a specific field (Vanni et al. 2014). The network was described by the total number of links (two authors connected) and degree of each node (author), which was represented by the number of direct connections with other authors. These analyses were conducted in R using igraph and network packages.

Impact of articles in scholarly publications. The visibility and influence of the SAD articles in scholarly publications were assessed by citation metrics analysis using Google Scholar, which is known to provide the most comprehensive coverage when compared with Web of Science and Scopus (de Winter et al. 2014; Harzing and Alakangas 2016). For example, the Web of Science focuses on journals with a certain impact factor, whereas Google Scholar includes languages other than English, whenever available on the web (Pautasso 2016). The number of cites that an article received from its publication date was obtained from a search by article title (as of 30 January 2017). The impact of the research was not based solely on the total number of cites per article, to avoid time-related bias, but primarily on the cites/year (total cites divided by the number of full calendar years since publication).

RESULTS

Number of studies and SAD. The two search engines returned 257 records, which were reduced to 97 after the removal of duplicates and articles that were not related to plant disease assessment. Of these, five were excluded because they did not conform to the three primary criteria of the study. A further 13 studies were included after scrutinizing the literature cited in the articles found with the search engines. In total, 105 studies were eligible for the review of methods (Table 2). The majority of these studies reported one SAD set for a single disease. However, in 17 studies, two or more SAD sets were reported as representing different diseases, number of diagrams, color schemes, symptom shapes, and patterns or organs (Table 2). For this reason, the final number of individual SAD across the 105 studies was 127.

Authorship: country, journals, and language trends. Research groups from 10 countries authored the studies but 90 of 105 studies originated from Brazilian research groups. Other countries included Mexico (4 studies), the United States (3), New Zealand (2), Chile (1), China (1), Colombia (1), Kenya (1), Spain (1), and Tanzania (1). Most studies were published in Brazilian journals and were in Portuguese. Three Brazilian journals (Summa Phytopathologica, Tropical Plant Pathology [formerly Fitopatologia Brasileira], and Ciência Rural) accounted for 49.5% (52 of 105) of the studies; and only five of those were written in English. Other journals with more than three studies included the European Journal of Plant Pathology (9 studies), Journal of Phytopathology (4), and Plant Pathology (4). In total, 60 studies were written in Portuguese, 41 in English, two in Spanish, and one in both English and Spanish. Nonetheless, there was an increasing trend over the years toward publishing in English (25 of 36) after 2012 (Fig. 1). Prior to 2006, the annual number of articles published was usually less than four but increased to approximately eight studies per year thereafter, with the exception of 2012 and 2016 (fewer than five published) (Fig. 1). Most articles were published as original research articles (82 of 105) and the remainder as short communications (23 of 105).

Frequency of authors and coauthorship network. The mean and the median numbers of authors per article were 4.63 and 5.0, respectively. The minimum and maximum numbers of authors were one and eight, respectively, but 50% of the articles were coauthored by three to six scientists. The number of unique authors in the collection was 327 but the great majority (77%) authored only one article, 13.1% authored two articles, 9.7% three articles, 4.8% four articles, and only 3.2% authored five or more articles (Fig. 2). The mean numbers of authors in the publications ranged from 4.4 to 6.14 across the 10 most prolific authors (Table 3). The coauthorship network was composed of 1,019 links, with a mean degree (number of connections) of 6.25 across the 327 nodes (authors) (Fig. 3; Table 3). The maximum degree was 51 for the most prolific author, meaning this author also had the largest collaboration network, followed by other authors linked to at least 20 coauthors. A visual inspection of the network suggests that some authors were focused within their own research community (usually a department or graduate program), whereas others were bridges connecting two or more research communities (Fig. 3). Six large communities were identified according to the region or institute of the leading author, and contain the majority of the articles (n = 84) (Fig. 3). The remainder of the articles were not connected to these communities and represent an isolated article or small communities centered on a local leading author (Fig. 3).

Publication impact of SAD articles. The total number of citations retrieved from Google Scholar was 1,475. There was a considerable variation in the number of cites among the articles. The mean and median citations/article were 14.05 and 7.0, respectively.

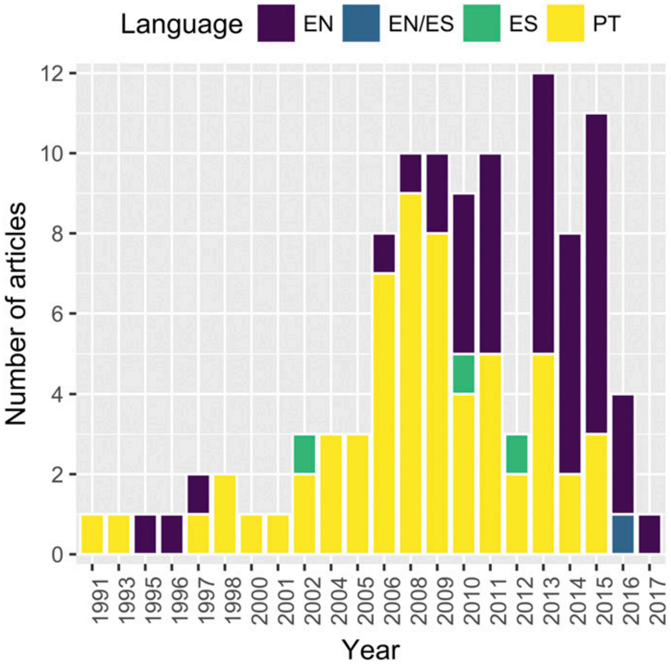

Fig. 1. Frequency distribution of 105 peer-reviewed articles, published between 1991 and 2017, reporting construction and/or validation of standard area diagrams (SAD), and which were selected following a systematic review on peer-reviewed publications in English (EN), Portuguese (PT), or Spanish (ES).

There were 14 articles with zero citations and 30 articles with at least five citations. The 10 most highly cited articles had >40 citations and were all published >10 years ago, including the most cited soybean rust SAD study, which had 164 citations (Godoy et al. 2006). The number of cites per year averaged 1.5 cites/year, with a maximum of 14.9 cites/year (soybean rust SAD). There was a general trend for the most cited articles being the ones with more cites per year. However, the second most influential article was the pecan scab

TABLE 2. Summary information on the characteristics of standard area diagrams (SAD) in studies published in the plant pathology literature from 1991 to 2017 following a systematic review based on three criteria: (i) the plant diseases and causal agents being clearly defined, (ii) the development of the SAD being fully described, and (iii) the SAD being displayed with each diagram of the set depicting a percent severity

Crops[a]	Pathogen names[b]	*N*[c]	O[d]	SAD[e]	Cl[f]	Il[g]	Min[h]	Max[i]	Authors
Apple	*Colletotrichum gloeosporioides*	1	L	D	Bw	6	0.08	30.9	Kowata et al. (2010)
Apple	*Gloeodespomigena/Schizathyriumpomi*	1	F	D	Gs	10	0.4	65	Spolti et al. (2011)
Arracacha	*Septoria apiicola/Cercospora arracacina*	1	L	D	Bw	7	0.7	53	Mesquini et al. (2009)
Barbados cherry	*Corynespora cassiicola*	1	L	P	True	6	2	48	Celoto and Papa (2010)
Beach morning-glory	*Cercospora abamensis*	1	L	P	Gs	6	0.34	22.5	Pethybridge and Nelson (2015)
Bean	*Colletotrichum lindemuthianum/Uromyces appendiculats/Phaeoisariopsis griseola/Alternaria* sp.	4[j]	L	D	Bw	9	0.1	24	Godoy et al. (1997)
Bean	*Xanthomonas campestris* pv. *phaseoli*	1	L	P	True	8	0.97	51	Diaz et al. (2001)
Beet	*Cercospora beticola*	1	L	D	Bw	6	0.41	23.6	May De Mio et al. (2008)
Cactus	*Alternaria tenuis*	1	Cl	D	Bw	6	2	40	Lima et al. (2011)
Cashew	*Oidium anacardii*	3[k]	L	D	Bw	5	1	50	Nathaniels (1996)
Cashew	*Cryptosporiopsis* spp.	1	L	P	True	6	0.2	67.4	Menge et al. (2013)
Cassava	*Cercosporidium henningsii*	1	L	D	Bw	6	1	32	Michereff et al. (1998)
Castor bean	*Amphobotrys ricini*	1	Bu	D	Bw	5	8	100	Chagas et al. (2010)
Castor bean	*Cercospora ricinella*	1	L	D	Bw	4	0.1	45	Santos et al. (2009)
Castor bean	*Amphobotrys ricini*	1	Bu	P	True	10	3	100	Sussel et al. (2009)
Chirimoyo	*Colletotrichum gloeosporioides*	1	L	P	True	6	1	75	Tovar-Soto et al. (2002)
Chrysanthemum	*Puccinia horiana*	1	L	D	Bw	6	1	30	Barbosa et al. (2006)
Citrus	*Xylella fastidiosa*	2[l]	L	D	Bw	6	3	64	Amorim et al. (1993)
Citrus	*Citrus leprosis virus*	1	L	D	Bw	5	0.39	39.5	Rodrigues et al. (2002)
Citrus	*Guignardia citricarpa*	1	F	D	Bw	6	0.5	68	Spósito et al. (2004)
Citrus	*Mycosphaerella citri*	1	L	D	Bw	6	1	36	Silva et al. (2009)
Citrus	*Alternaria alternata*	1	F	D	Gw	6	0.1	25	Renaud et al. (2008)
Citrus	*Xanthomonas axonopodis* pv. *citri*	1	L	D	3-col	8	0.2	30	Belasque Júnior et al. (2005)
Citrus	*Xanthomonas citri* subsp. *citri*	2[m]	F	D	3-g	5	0.5	40	Braido et al. (2014a)
Citrus	*Xanthomonas citri* subsp. *citri*	2[m]	F	D	2-col	5	0.7	39	Braido et al. (2014b)
Coffee	*Phoma tarda*	1	L	P	True	8	1.3	50	Salgado et al. (2009)
Coffee	*Cercospora coffeicola*	1	L	P	True	6	0.7	49	Custódio et al. (2011)
Coffee	*Pseudomonas syringae* pv. *garcae*	1	L	P	True	8	0.4	45.1	Belan et al. (2014)
Coffee	*Colletotrichum gloeosporioides*	1	L	D	True	11	0.5	46.9	Freitas et al. (2015)
Coffee	*Hemileia vastatrix*	1	L	D	2-col	6	2.5	80	Capucho et al. (2011)
Coffee	*Cercospora coffeicola*	2	F	P	True	13	2	70	Azevedo de Paula et al. (2016)
Common bean	*Pseudocercospora griseola*	1	L	D	True	9	0.1	60	Librelon et al. (2015)
Cotton	*Ramularia gossypii*	1	L	P	True	9	0.05	67.2	Aquino et al. (2008)
Cowpea	*Entyloma vignae*	1	L	D	Bw	6	1.5	45	Michereff et al. (2006a)
Cowpea	*Cercospora cenescens*	1	L	D	Bw	8	1	82	Albert et al. (2008)
Cowpea	*Xanthomonas axonopodis* pv. *vignicola*	2[n]	L	D	2-col	6	0.05	17.7	Lima et al. (2013)
Cucumber	*Corynespora cassiicola*	1	L	P	True	7	0.3	46	Teramoto et al. (2011)
Custard apple	*Colletotrichum gloeosporioides*	1	L	D	Bw	6	1	40	Correia et al. (2011)
Eggplant	*Phomopsis vexans*	1	L	D	Bw	8	0.5	32	Correia et al. (in press)
Eucalyptus	*Teratosphaeria nubilosa*	2[o]	L	D	Bg	6	3	84	Passador et al. (2013)
Eucalyptus	*Quambalaria eucalypti*	1	L	D	Bw	8	1	32	Andrade et al. (2005)
Eucalyptus	*Oidium eucalypti*	1	L	P	True	12	0.3	48.7	Valeriano et al. (2015)
Eucalyptus	*Cylindrocladium* spp.	2[p]	L	D	2-col	8	1.84	83.7	Damasceno et al. (2014)

(*continued on next page*)

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[a] Common name as published, in alphabetical order.

[b] Binomial as published.

[c] Number of SAD reported in the article. When more than one SAD set is represented (i.e., a multipanel), the reasons are provided in footnotes j through t.

[d] Organ type designation: L = leaf, Ll = leaflet, F = fruit, Cl = cladodes, Bu = bunch, Br = bractea, Stm = stem, Stk = stalk, and Spk = spike.

[e] SAD presented as a drawing (D) or as an image from a photograph (P) of the symptomatic organs.

[f] Color (Cl) scheme of the diagram set: Bw = black and white, Bg = black and gray, Gs = grayscale, True = true color, 2-g = two shades of gray, 3-g = three shades of gray, 2-col = two color, and 3-col = three color.

[g] Number of illustrations (Il) of the severities represented in the SAD.

[h] Minimum severity in the SAD, excluding representations of zero severity.

[i] Maximum severity in SAD.

[j] SAD depicting different diseases described and a SAD presented for each on that crop.

[k] SAD depicting disease on different plant organs.

[l] SAD depicting different maximum severities.

[m] SAD depicting different numbers of illustrations (five or six).

[n] SAD depicting different organ shapes or perspectives.

[o] SAD depicting disease on immature or adult leaves.

[p] SAD depicting different color schemes (monochrome or true color).

[q] SAD depicting two different color schemes, such as black and white or two colors (e.g., green and brown).

[r] SAD depicting different crops and diseases.

[s] SAD depicting two-color schemes by two incremental scales (log or linear).

[t] SAD depicting disease on different organ types.

SAD study (Yadav et al. 2013), with 6.5 cites/year during the 4 years since publication (26 citations total). Other SAD with at least five citations were soybean late-season diseases and foliar diseases of common bean SAD, published more than 10 years ago (Fig. 4).

Crops, organs, diseases, and pathogens. The 127 SAD represented diseases on 48 crops and, therefore, some crops had more than one SAD for different diseases of the same crop (Table 2). The crop with the highest number of SAD was citrus (11 SAD), followed by tomato, maize, grapevine, soybean, eucalyptus, rice, and bean,

TABLE 2. (*continued from preceding page*)

Crops[a]	Pathogen names[b]	*N*[c]	O[d]	SAD[e]	Cl[f]	Il[g]	Min[h]	Max[i]	Authors
Grapevine	*Xanthomonas campestris* pv. *viticola*	1	L	D	Bw	8	2	91	Nascimento et al. (2005)
Grapevine	*Isariopsis clavispora*	1	L	D	Bw	6	1.6	40.2	Lenz et al. (2009a)
Grapevine	*Plasmopara viticola*	2[q]	L	D	2-col	7	1	75	Buffara et al. (2014)
Grapevine	*Phakopsora euvitis*	2[q]	L	D	2-col/Bw	6	1	75	Angelotti et al. (2008)
Grapevine	*Botrytis cinerea*	1	Bu	D	2-g	12	1	90	Hill et al. (2010)
Lettuce	*Cercospora longissima*	1	L	D	Bw	8	1	68	Gomes and Michereff (2004)
Loquat	*Fusicladium eriobotryae*	1	F	D	Bw	8	2	98	González-Domínguez et al. (2014)
Maize	*Exserohilum turcicum*	1	L	D	Bw	8	0.5	96	Vieira et al. (2014)
Maize	*Colletotrichum graminicola*	1	Stk	P	Gs	8	6.2	93.8	Nicoli et al. (2015)
Maize	*Kabatiella zeae*	1	L	D	True	7	0.9	51	Camochena et al. (2008)
Maize	*Phaeosphaeria maydis*	1	L	P	True	7	1.1	39.7	Malagi et al. (2011)
Maize	*Phaeosphaeria maydis*	1	L	P	True	8	1	79	Sachs et al. (2011)
Maize	*Exserohilum turcicum*	1	L	P	True	7	0.5	54	Lazaroto et al. (2012)
Maize	*Pantoea ananatis*	1	L	D	2-col	9	0.1	64	Capucho et al. (2010)
Maize	*Phyllachora maydis/Monographella maydis*	1	L	P	True	6	1	100	Ramos and Islas (2015)
Melon	*Pseudoronospora cubensis*	1	L	D	Bw	8	2	96	Michereff et al. (2009)
Mentha	*Puccinia menthae*	1	L	D	Bw	6	0.4	37.5	Eschamps et al. (2008)
Papaya	*Asperisporium caricae*	1	F	D	Bg	8	0.1	20	Vivas et al. (2010)
Papaya	*Streptopodium caricae*	1	L	D	2-g	6	0.6	20	dos Santos et al. (2011)
Papaya	*Colletotrichum gloeosporioides*	1	F	P	True	6	1.78	60.9	Zavala-León and Cristóbal-Alejo (2013)
Pea/Potato	*Erysiphe pisi/Peronospora viciae/Spongospora subterranean* s. *subterranea*	3[r]	L	D	Bw	10	5	100	Falloon and Rollinson (1995)
Peach	*Tranzchelia discolor*	1	L	D	2-col	10	0.1	30	Dolinski et al. (in press)
Peach	*Wilsonomyces carpophilus*	1	L	D	Bw	6	0.25	24.2	Challiol et al. (2006)
Peach	*Xanthomonas arboricola* pv. *pruni*	1	L	D	Bw	6	0.5	55.3	Citadin et al. (2008)
Pear	*Entomosporium mespili*	1	L	D	Bg	7	0.3	40	Nunes and Alves (2012)
Pecan	*Fusicladium effusum*	1	F	D	Bw	10	1.5	91	Yadav et al. (2013)
Potato	*Alternaria grandis*	1	L	D	2-col	10	0.1	100	Duarte et al. (2013)
Rice	*Bipolaris oryzae*	1	L	D	Bw	6	1.6	38.6	Lenz et al. (2010)
Rice	*Bipolaris oryzae*	4[s]	L	P	True/bw	7	0.5	36	Schwanck and Del Ponte (2014)
Roselle	*Corynespora cassiicola*	2	L/Cal	P	True	5	2	70	Ortega-Acosta et al. (2016)
Rubber tree	*Oidium hevea*	1	L	D	Bw	6	2.5	50	Tumura et al. (2013)
Soybean	*Corynespora cassiicola*	1	L	D	Bg/True	7	1	52	Soares et al. (2009)
Soybean	*Septoria glycines/Cercospora kikuchii*	1	L	D	Bw	5	2.4	66.6	Martins et al. (2004)
Soybean	*Phakopsora pachyrhizi*	1	L	D	Bw	6	0.6	78.5	Godoy et al. (2006)
Soybean	*Peronospora manshurica*	1	L	D	Bw	8	0.08	87.6	Kowata et al. (2008)
Soybean	*Sclerotinia sclerotiorum*	1	Stm	D	2-col	5	2	70	Juliatti et al. (2013)
Soybean	*Cercospora sojina*	1	L	D	2-col	8	0.1	39.9	Debona et al. (2015)
Soybean	*Cercospora sojina*	2	L	P	True/Gs	10	2	18	Price et al. (2016)
Strawberry	*Dendrophoma obscurans*	1	L	D	Bw	6	0.9	79.5	Mazaro et al. (2006a)
Strawberry	*Mycosphaerella fragariae*	1	L	D	Bw	5	0.11	34.9	Mazaro et al. (2006b)
Sugarcane	*Diatraea saccharalis/Fusarium moniliforme/Colletotrichum falcatum*	1	Stk	D	3-col	8	4	92	Giglioti and Canteri (1998)
Sugarcane	*Puccinia kuehnii*	1	L	D	True	9	0.06	45	Klosowski et al. (2013)
Sunflower	*Alternaria helianthi*	1	L	D	Bw	9	0.03	66	Leite and Amorim (2002)
Sunflower	*Septoria helianthi*	1	L	D	Bw	5	2	71	Lenz et al. (2009b)
Sweet pepper	*Cercospora capsici*	1	L	D	Bw	6	1.5	50	Michereff et al. (2006b)
Sweet pepper	*Colletotrichum gloeosporioides*	1	F	D	Gs	8	1	80	Pedroso et al. (2011)
Tomato	*Xanthomonas campestris* pv. *vesicatoria*	1	L	D	Bw	5	1	50	Mello et al. (1997)
Tomato	*Stemphylium solani/Alternaria solani*	2[j]	L	D	Bw	5	2	32	Boff et al. (1991)
Tomato	*Leveillula taurica*	2[t]	L/Ll	D	3-g	6	1	60	Lage et al. (2015)
Tomato	*Phytophthora infestans*	1	L	D	2-col	6	3	77	Corrêa et al. (2009)
Tomato	*Xanthomonas euvesicatoria*	1	L	D	2-col	12	0.5	90	Duan et al. (2015)
Tomato	*Leveillula taurica/Erysiphe* sp.	1	L	D	Bg	5	2.4	66.6	Sepúlveda-Chavera et al. (2013)
Torch ginger	*Colletotrichum gloeosporioides*	1	Br	D	Bw	9	1	92	Barguil et al. (2008)
Watermelon	*Didymella bryoniae*	1	L	D	Bg	5	10	90	Sousa et al. (2014)
Watermelon	*Cercospora citrullina*	1	L	P	True	8	2	93	Halfeld-Vieira and Nechet (2006)
Wheat	*Bipolaris sorokiniana*	1	L	P	True	11	0.1	83	Domiciano et al. (2014)
Wheat	*Pyricularia oryzae*	1	Spk	P	True	9	3.5	100	Maciel et al. (2013)
Wheat	*Pyricularia oryzae*	1	L	D	2-col	10	0.1	72	Rios et al. (2013)
Wheat	*Puccinia triticina*	1	L	D	2-col	10	0.1	95	Alves et al. (2015)
Yam	*Curvularia eragrostidis*	1	L	D	Bw	6	1	32	Michereff et al. (2000)
Yellow passion fruit	*Colletotrichum gloeosporioides*	1	F	D	Bw	6	1	70	Fischer et al. (2009)

each with at least five SAD (Table 2). In most cases, the SAD represented symptoms on the leaves (99 of 127), followed by single fruit (16 of 124), bunches of fruit (3 of 116), and an additional seven organs with at least one SAD (Table 2). For citrus, six SAD were developed for disease symptoms affecting fruit and five for those affecting leaves. Other less common organs of specific plant species represented in the SAD included cladodes of cactus, bracts of torch ginger, blossom of cashew, wheat spikes, maize stalks, soybean stems, and potato tubers (Table 2).

In total, 103 diseases were represented in the SAD and these were mostly caused by fungi (103 of 127) that produced various symptoms, with leaf spots, leaf blotches, rusts, and anthracnose being most frequent. There were 17 SAD depicting diseases caused by bacteria of the genera *Xanthomonas*, *Pseudomonas*, *Pantoea*, and *Xylella*. Six SAD were reported for diseases caused by oomycetes, of which the majority was due to downy mildews and late blight. One SAD was developed for symptoms caused by *Citrus leprosis virus* (Table 2). There were five examples of more than one study, by different research groups, reporting a SAD for the same disease and plant organ. These pathosystems were *Xanthomonas citri* pv. *citri* in citrus, *Amphobotrys ricini* in castor bean, *Phaeosphaeria maydis* in maize, *Cercospora sojina* in soybean, and *Bipolaris oryzae* in rice (Table 2).

SAD development. *Number of samples and measurement of the actual severity.* The SAD were developed primarily from symptomatic organs sampled from plants grown in the field but, in a few cases, from symptomatic organs from plants inoculated under greenhouse conditions (data not shown). The mean and median numbers of samples used to develop the SAD within each study were 175.2 and 100, respectively (25th and 75th percentiles = 100 and 200, respectively). In one exceptional case, 2,398 samples were used for SAD development for one disease (Table 2).

The method used to measure actual severity was reported in 103 of 105 studies. Digitized images of the symptomatic organs (from scanners or digital cameras) were the most common method

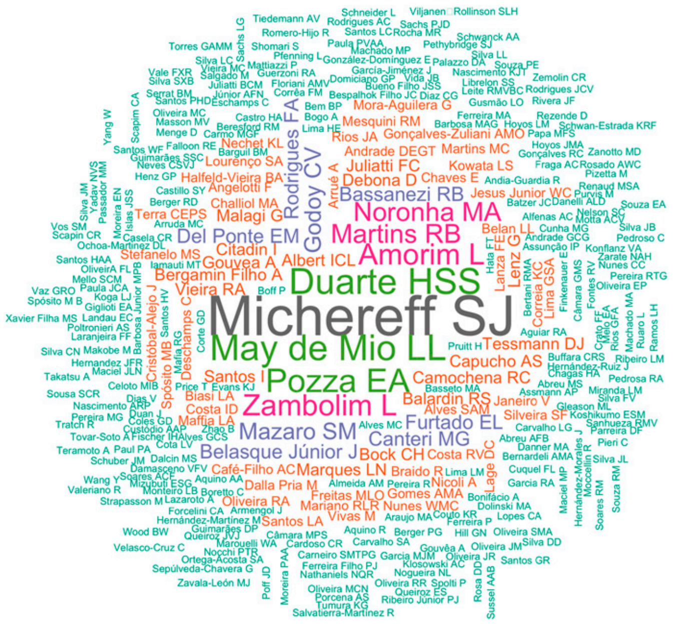

Fig. 2. Word-cloud of authors of 105 articles on the development or validation of standard area diagrams for aiding visual assessment of plant disease severity, which were published from 1991 to 2017 in 33 peer-reviewed journals. The size of the author's name is proportional to the number of articles (1 to 15 articles).

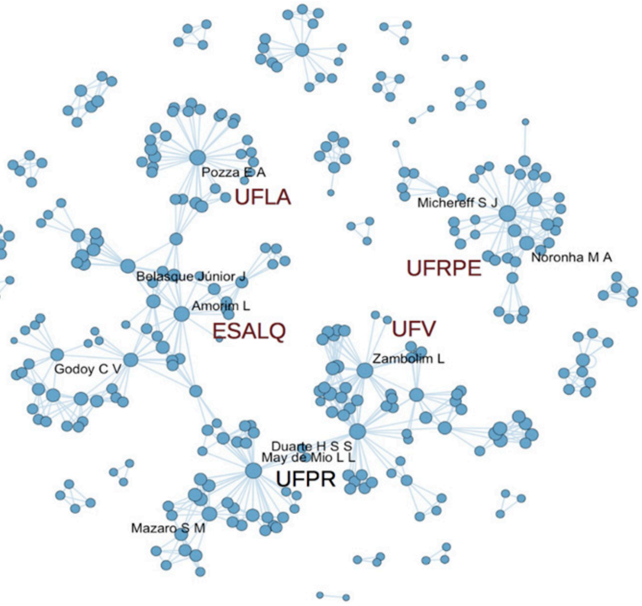

Fig. 3. Coauthorship network for 105 scientific articles reporting the development or validation of standard area diagrams published from 1991 to 2017 in 33 peer-reviewed journals. Nodes (circles) represent authors linked (lines) to another author in the same article. The size of the node is proportional to the number of links. The 10 most prolific authors published from 5 to 15 articles and were linked to 20 to 51 authors (Table 3). Five Brazilian institutions that offer graduate courses in plant disease epidemiology are indicated together with the respective faculty leader.

TABLE 3. Citation and network statistics for the 10 most prolific authors of articles describing the development and validation of standard area diagrams illustrating plant disease severity and published in peer-reviewed literature from 1991 to 2017

		Article and authorship (*n*)			
Author	Institution[a]	Articles	Mean authors/article	Mean (SD) cites/year[b]	Degree[c]
Michereff	UFRPE	15	4.4 (3 to 6)	15.1 (15.9)	51
Duarte	UFPR (UFV)	9	5.4 (4 to 8)	7.6 (7.0)	40
May De Mio	UFPR	9	5.4 (4 to 7)	6.1 (4.7)	40
Pozza	UFLA	8	5.2 (3 to 6)	6.1 (6.2)	34
Amorim	ESALQ	7	5.1 (2 to 7)	58.0 (28.2)	29
Zambolim	UFV	7	6.1 (3 to 8)	12.1 (9.9)	36
Martins	UFAL	6	5.0 (4 to 6)	7.1 (10.1)	24
Noronha	UFAL	6	4.5 (3 to 6)	18.1 (14.0)	21
Godoy	EMBRAPA	5	5.0 (3 to 7)	64.4 (67.5)	20
Mazaro	UTFPR	5	5.6 (3 to 7)	7.4 (5.7)	23

[a] UFRPE = Universidade Federal Rural de Pernambuco, UFLA = Universidade Federal de Lavras, ESALQ = Escola Superior de Agricultura Luiz de Queirós, UFV = Universidade Federal de Viçosa, UFAL = Universidade Federal de Alagoas, UFPR = Universidade Federal do Paraná, and UTFPR = Universidade Teconológica Federal do Paraná.

[b] Citation metrics, calculated based on the number of citations provided by Google Scholar as of 30 January 2017, with standard deviation (SD) in parentheses.

[c] Network description: degree of connectivity between authors based on the number of direct connections.

(82 of 103 reports). However, there was a lower frequency of reports that used hand-drawn diagrams of symptoms on paper (4 of 103) or plastic (17 of 103), where actual severity was measured using a leaf area meter or other manual method. Regardless of method, actual severity was determined based on the symptom/total area ratio using different procedures that included a range of image analysis software. The most commonly used software for measuring actual severity was QUANT (29 of 101), followed by APS-Assess (21 of 101), and the LI-COR leaf area meter (13 of 101). Fourteen additional licensed computer programs, including WinRHIZO, Image Tool, and AutoCAD, were used in more than four studies, and custom-made software was used in two studies to measure disease severity (Fig. 5). The nonsoftware-based measures of actual severity included planimeter, graph paper, counting the number of diseased subunits, and indirect measures of disease severity by weight measurement of total leaf area and lesion area (Fig. 6).

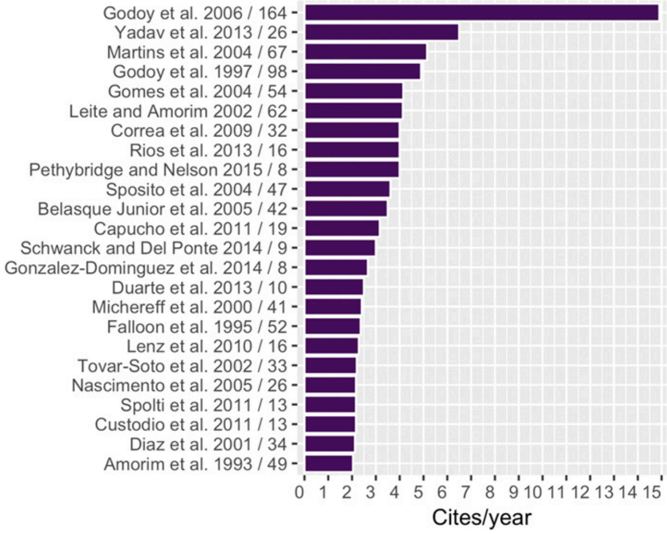

Fig. 4. Number of citations per year after publication of articles on the development or validation of standard area diagrams, with a minimum of two cites per year. The number of cites was retrieved from Google Scholar on 30 January 2017. These articles are a subset of 105 articles selected following a systematic review of studies published between 1991 and 2017. The articles are represented by the author-date citation and total number of cites.

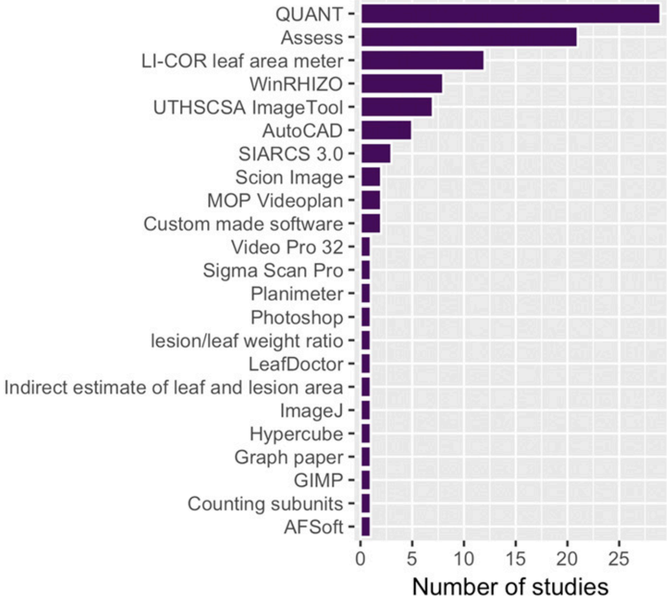

Fig. 5. Frequency distribution of methods used to measure actual plant disease severity reported in 105 articles on the development or validation of standard area diagrams as a tool to aid visual assessment of plant disease severity. Articles were selected following a systematic review of studies published between 1991 and 2017.

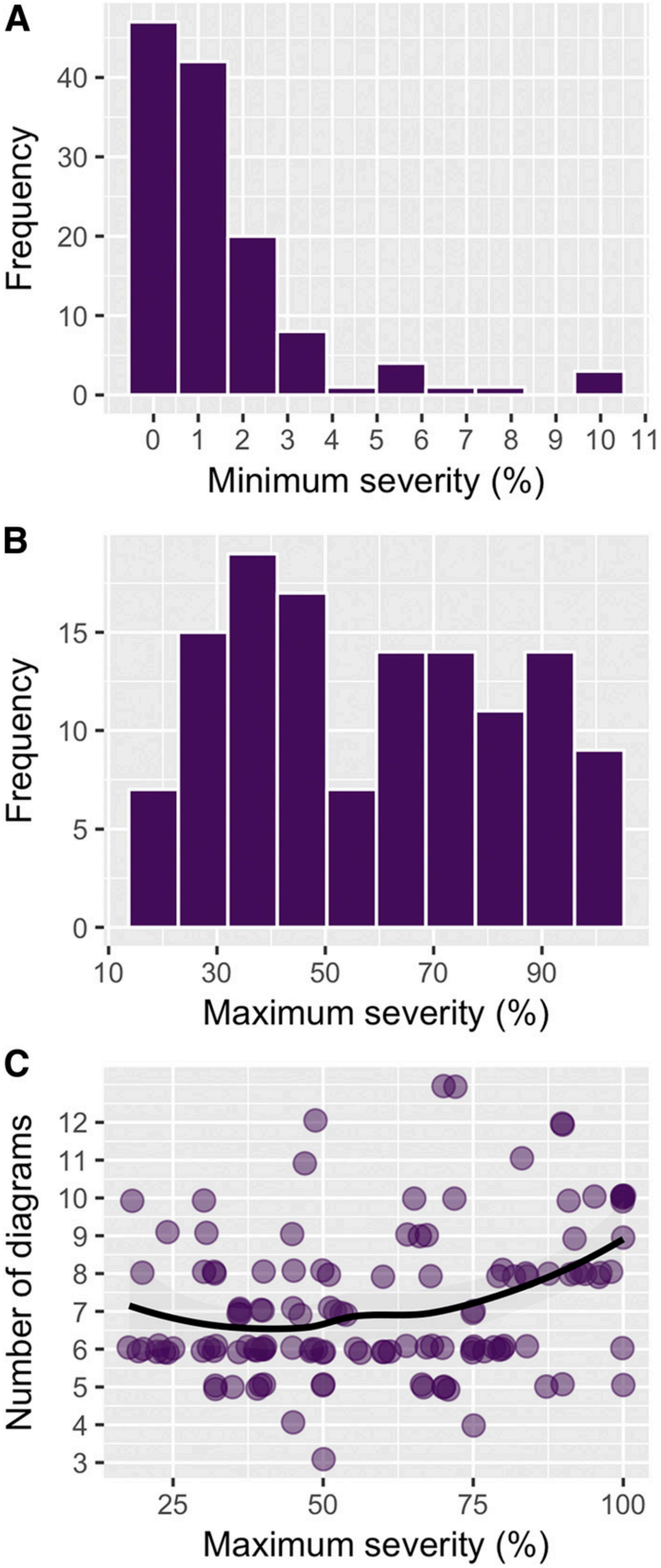

Fig. 6. Frequency distribution of standard area diagrams ($n = 116$) for aiding visual severity estimates according to specific characteristics: **A,** minimum severity; **B,** maximum severity; and **C,** relationship between **B** and **C**. The smooth line and shaded areas in C represent a loess smoothing (local fitting) curve.

SAD representations and color scheme. The majority of SAD were displayed as a single panel (106 of 127). However, 18 SAD used two (15 of 127), three (2 of 116), or four (1 of 116) representations for the same disease. A large portion (57 of 127) of SAD were drawn by hand in black and white or using stylized disease patterns found on a subsample of diseased leaves by image analysis. In total, 31 of 127 SAD were depicted in true colors, using the original color photographs. Alternative color schemes involved a different combination of two to three colored or grayish areas representing healthy and diseased tissue (Table 2).

Number of diagrams and incremental scale. The number of individual diagrams depicting a specific percent severity (reference of actual severity) for the plant organ in the diagram set ranged from 3 to 13. The most frequent number of diagrams was six (45 of 127), followed by eight and five diagrams in >15 SAD (Table 2). Most frequently, the minimum severities depicted in the SAD were <3% severity; however, there were a few diagrams where the minimum severity was 5 to 10% (Fig. 6A; Table 2). The maximum severity depicted in the diagram set was 17.7 to 100% (Fig. 6B; Table 2) and there was a moderate positive association with the mean number of diagrams ($r = 0.30$, $t = 3.59$, df = 125, $P = 0.0004$) (Fig. 6C).

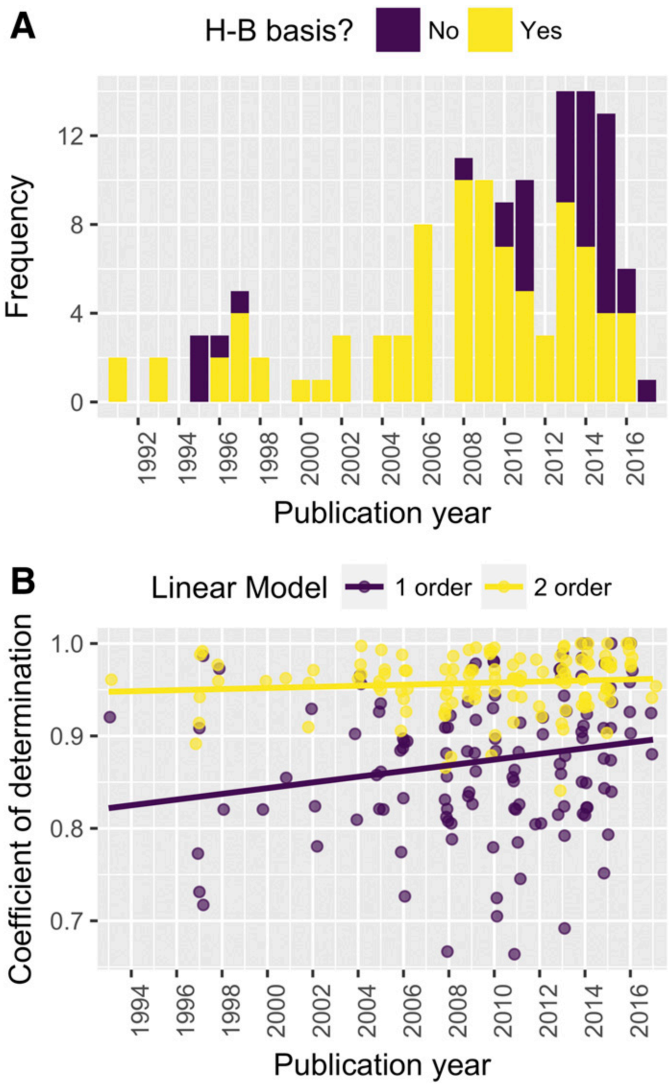

Fig. 7. A, Frequency of articles, ordered by year of publication, in peer-reviewed journals during the period 1992 to 2017 on the development of standard area diagrams (SAD) for aiding visual severity estimation and that invoked the use of the Horsfall-Barratt scale or Weber-Fechner law as rationale for the incremental scale between severities. **B,** For each SAD, first-order (1 order) and second-order (2 order) linear regression models were fitted to the relationship between severity of each diagram and the position of the diagram in the set. The coefficient of determination (R^2) was used to indicate whether the incremental grades approximated a linear or nonlinear scale. Lines depict the estimated R^2 based on a linear regression model fitted to the data over time. The estimated increase in the R^2 of the first-order model over the years was significant ($P = 0.022$). The total number of articles was 105.

The incremental severities in the set followed a nonlinear trend for most of the SAD. The principles of the H-B scale and Weber-Fechner law were explicitly invoked in the introduction or methodology as the basis to define the severity increments in 90 of 127 of the SAD. For the remainder (37 of 127), there was either no information or an approximately linear scale was used, with additional diagrams represented at low severities (<10%). Generally, the rationale stated for providing additional diagrams at low severities was that this was the range where the greatest resolution of severity is required for differentiating treatments of interest or predicting disease severity. In recent years, there was a trend toward a lower proportion of studies explicitly invoking the H-B scale or Weber-Fechner law (Fig. 7A). When first- and second-order (quadratic) linear models were fitted to the relationship between severity and diagram number in the set, as indicative of which increments were used, the second-order provided the best fit based on the coefficient of determination (R^2) (Fig. 7B). However, there was a significant trend ($P = 0.02$) of increasing values of R^2 for the first-order model fitted to the relationship over time. For 29 SAD, the R^2 for the first- and second-order linear models approximated to equal (within a 0.03 range), indicating a more uniform interval between adjacent diagrams for most of the values and, thus, a more linear distribution of SAD.

SAD validation. *Overall validation approach and rater experience.* The majority (96 of 105) of the studies published after 1990 included a validation of the method upon implementation and a validation of the SAD was not performed in only 9 studies in the dataset. In 18 of the validation studies, the estimates were made only aided (i.e., using SAD) but lacked validation in the absence of the SAD, precluding a measure of improvement in estimation. For the remaining 78 studies, a prepost test design (estimates unaided and repeated using the SAD aid by the same rater) was used to determine whether there was any improvement in accuracy. For these studies, the number of raters ranged from 1 to 40, with a median of 9.5 raters and an interquartile range of 4 (between 6 and 10). In 61 studies, raters were previously classified according to experience in disease assessments. There were 815 raters who provided two estimates (unaided and aided estimates), with 513 assigned as inexperienced, 137 as experienced, and no information provided on the experience of the remaining 165 raters. There were 38 studies that used only inexperienced raters, 3 used only experienced raters, and 20 used both experienced and inexperienced raters during validation.

Validation statistics for accuracy and reliability. The most commonly used metrics for assessing accuracy and precision of the unaided and aided estimates in 96 studies were the coefficients of linear regression (80 of 96), followed by Lin's CC coefficients (14 of 96). Only two studies reported these two metrics for the same data (2 of 96). Eight studies did not report a validation metric. For the set of studies that included both unaided and aided estimates, all but two reported the R^2 and the regression coefficients (intercept and slope). One study reported only the R^2 value and one other study reported the R^2 and the slope only. There was a trend of increasing use of Lin's CC statistics during the last 5 years (Fig. 8). The two measures of reliability reported in the studies were the interrater reliability in 42 of 105 studies and the intrarater reliability in 15 of 105 studies. The metric used to indicate the reproducibility of the estimates for either only aided estimates or unaided and aided (the majority) was reported for 42 studies. For three studies, there were no data available. The metric most commonly used alone to indicate reproducibility was the R^2 value to describe the relationship between the unaided or aided estimates for all possible pairs of raters (used in 24 studies). The less frequently used method alone was the intraclass correlation coefficient (ICC) (only five studies). In 11 studies, both the R^2 value and the ICC were reported. In 10 other studies, the indicators included R^2 but only reported for one selected rater (1 study); R^2, intercept, and slope for all pairs of raters (2 studies); R^2, intercept, and slope for one selected rater (2 studies); the mean R^2 for all the raters combined (not the matrix) (1 study); and the frequencies of classes of R^2 (4 studies).

DISCUSSION

The use of SAD for aiding visual assessment of disease severity gathered momentum from sentinel work during the 1960s, which provided generic guidelines for SAD development (James et al. 1968; Large 1966). Two decades later, Campbell and Madden (1990) reviewed and listed published SAD and discussed their importance in phytopathometry. Bock et al. (2010) further reviewed the impact of SAD and discussed their importance in improving accuracy and reliability of disease estimates (Bock et al. 2016). To the best of our knowledge, this is the first comprehensive scientometric analysis and quantitative summary of pathosystems and trends in methods for SAD development and validation reported in the peer-reviewed literature during the last 25 years.

The majority of the SAD originated from studies conducted by Brazilian scientists and were published in peer-reviewed local journals in the Portuguese language. The prevalence of SAD research in Brazil was previously noted but reasons for this were not explored (Bock et al. 2010). Network analysis revealed connection patterns among coauthors and a significant contribution of a half-dozen prolific authors who are faculty members of agronomy and plant pathology departments with graduate programs in Brazil. Historically, Brazilians were among the first to popularize the use of regression analysis to validate SAD in the early literature (1990s) to improve accuracy and precision of severity estimates (Amorim et al. 1993; Godoy et al. 1997; Michereff et al. 1998). More cost-effective tools for measuring actual values (e.g., leaf area meters and image analysis software) and statistical methods for validating SAD were available by that time. Thus, the relatively straightforward experimental work required to produce and validate SAD—after preparing the diagram with illustrations of a range of disease severity—and publish the results in peer-reviewed journals boosted SAD development during the late 1990s. Therefore, SAD were developed for a burgeoning range of plant diseases, especially diseases of tropical crops that predominate in Brazil (Diaz et al. 2001; Leite and Amorim 2002; Martins et al. 2004; Mello et al. 1997; Michereff et al. 2000; Rodrigues et al. 2002) (Table 1) and for which standardized assessment methods were less established compared with diseases of crops from temperate regions (Campbell and Madden 1990).

The predominance of SAD reported from Brazil is almost certainly related to their popularity as components of graduate research projects; also, they were often published in national journals, which explains the peak in the number of publications in Portuguese during the mid-2000s. The coauthorship network shows that a few authors link two or more communities, because they appear to have moved from one community (as a graduate student) and have formed (as new faculty or a researcher at another institute) their own community alone or associated with others. However, a clear shift can be noted after 2010, when articles started to appear more often in international journals, which can be explained, at least in part, by the use of more rigorous scientific methods for SAD evaluation.

Measurement of the impact and usefulness of SAD as a practical tool to aid disease assessments or provide training is not straightforward. We focused on the number of citations provided by the more inclusive metrics provided by Google Scholar (as of January 2017). Among the 10 studies with at least four cites/year, most were published more than 6 years ago. The most cited SAD study (>14 cites/year), which is the soybean rust SAD published in a local Brazilian journal, is the best example of a timely and useful SAD for aiding severity estimates for a newly introduced disease of major economic impact to a region (Godoy et al. 2006). For this particular SAD, the citing articles primarily report fungicide test results (data not shown), which proliferated in the last decade and for which severity is a key variable and uniformity and accuracy in assessment is a requirement. The pecan scab SAD was published only recently (Yadav et al. 2013) but has received 26 citations as of January 2017. Two reasons are likely: (i) the article was published in a plant pathology journal (Plant Pathology) with a high impact factor and (ii) introduction of new hypothesis tests to determine the effect of SAD on accuracy and reliability (together with the work by Bardsley and Ngugi 2013 in the same issue) and deeper exploration of the ramification of errors in severity estimates by the use of concordance coefficients (Madden et al. 2007), which have been the statistics of choice in most of the subsequent SAD articles. Cases where other articles received notable numbers of citations were likely due to the significance of the disease, the overall impact factor of the journal, or the novelty of the technology. For example, the high citation rate for a recently published SAD for Cercospora leaf spot on beach morning-glory relates to an article describing an image analysis program for smartphones, which allows measurement of actual severity and generation of SAD from a handheld device (Pethybridge and Nelson 2015).

The frameworks used for SAD development were variable and likely to be influenced by when the study was conducted. For example, advances in image analysis and the availability of high-resolution, low-cost digital cameras (and, most recently, smartphones and "Leaf-Doctor") (Pethybridge and Nelson 2015) and specialized software combined with advances in statistical methods likely influenced the technological and analytical trends in SAD development. Although software has been developed to provide computer-generated diagrams (Nutter and Schultz 1995), most SAD found in our review have been developed based on analysis of diseased specimens from the field, primarily from naturally occurring epidemics, or by artificial inoculation of the host in a greenhouse.

Locally developed image analysis software may also have facilitated the early development of SAD, especially in Brazil, where the image analysis program QUANT predominated. The choice of software and instruments used to estimate actual disease severity

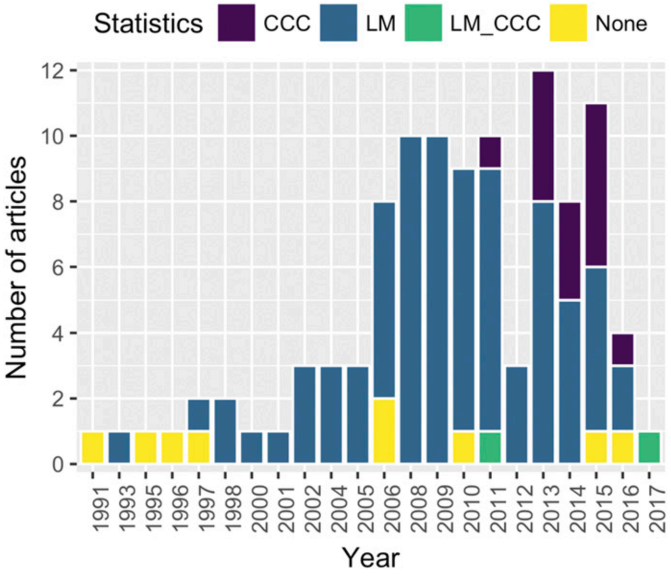

Fig. 8. Frequency of the statistical method (CCC = Lin's concordance correlation and LM = linear regression), used alone or in combination, to evaluate the agreement between visual estimates and actual disease severity in studies on the validation of standard area diagrams. Articles were selected following a systematic review of studies published between 1991 and 2017.

was likely dictated by availability and familiarity to the researcher. LI-COR leaf-area meters were used mostly prior to the advent of desktop computer software. APS Assess (Lamari 2002) has become a standard reference for estimation of disease severity and for comparisons with new tools (Barbedo 2014; Pethybridge and Nelson 2015). However, the true values obtained by digital image analysis must also be considered estimates because measurement relies on the subjective judgment of an expert to assign pixels as being healthy or diseased, which has been shown to vary across operators (reliability from 0.95 to 0.97) (Bock et al. 2008; Martin and Rybicki 1998) and across algorithms within different software (Barbedo 2014; Pethybridge and Nelson 2015).

The vast majority of the SAD were prepared as line drawings, mostly in black and white, and belonging to fungal diseases affecting two-dimensional plant parts such as leaves, corroborating observations of Campbell and Madden (1990). Specific approaches have been proposed for quantifying severity on the entire surface of a spherical structure (e.g., a fruit) such as specialized digital image capture and analysis of rotating specimens for facilitating the measurement of anthracnose severity on mango (Corkidi et al. 2006). However, the method has rarely being implemented and two-dimensional SAD remain the norm for fruit, with disease depicted on single or multiple fruit faces (Braido et al. 2014a,b; Spolti et al. 2011) and, likewise, for other reproductive structures such as bunches and spikes (Maciel et al. 2013; Sussel et al. 2009).

Disadvantages or inappropriateness of linear regression as an agreement method have been discussed (Bock et al. 2010; Lin 1989; Madden et al. 2007; Nita et al. 2003) but continue to be used. Lin's CC (Lin 1989) was suggested to be superior to linear regression for testing agreement in phytopathometry (Bock et al. 2010; Madden et al. 2007) and it was subsequently used in the analysis of SAD data. Initially, no hypothesis tests were used to compare data from prepost test experiments (Capucho et al. 2011; Spolti et al. 2011) but, later, NHST such as paired *t* tests and the equivalent nonparametric test (Kolmogorov-Smirnov) and a distribution-free bootstrapping procedure were further used to compare the means of each Lin's CCC statistic within and between raters (Bardsley and Ngugi 2013; Yadav et al. 2013). The availability of algorithms in statistical software (e.g., SAS and R) for performing concordance analysis and bootstrapping tests might have boosted their recent use, as suggested by 12 studies in our systematic review that have used concordance analysis since 2012 (Braido et al. 2014a,b; Debona et al. 2015; Domiciano et al. 2014; Duan et al. 2015; Duarte et al. 2013; González-Domínguez et al. 2014; Lage et al. 2015; Nicoli et al. 2015; Rios et al. 2013; Schwanck and Del Ponte 2014; Yadav et al. 2013).

BOX 1
Best practices for conducting and reporting studies on the validation of standard area diagrams (SAD) for aiding visual assessment of plant disease severity

- State and justify clearly the need and importance for designing SAD for a specific disease.
- Test hypothesis (see knowledge gaps in the discussion) related to SAD design and evaluation that may affect gains in accuracy and reliability of the severity estimates when using the aid.
- Sample a minimum number (e.g., $n = 100$) of specimens from natural epidemics representing the range of disease severity and typical symptoms observed. Do not use damaged, blemished specimens or those infected with other diseases. If the symptoms are induced by artificial inoculation, make clear limitations of use of the tool for assessing severity in field samples.
- Use standard image analysis software optimized to recognize and discriminate disease symptoms from healthy areas to calculate actual severity. If new tools are used or developed, provide evidence that the measurements are comparable with standard software.
- When designing the illustrations for the SAD set, ensure that the individual diagrams are prepared realistically, whether line drawn, actual photos, or computer generated. It is critical that the diagram allows the rater to discriminate easily between the diseased and healthy areas. The diagrams should preserve the characteristics of the symptoms for the range of severity found in the field.
- It is not established how many diagrams are required in a SAD set. We suggest that the number of diagrams should be no less than 6 and no more than 10, distributed approximately linearly, and spaced no more than 15% apart. Additional diagrams (±2) should be included between 0 and 10% severity, considering the tendency of raters to overestimate severity in this range, especially when symptoms consist of numerous small lesions.
- For validation, select at least 50 specimens representing the full range of actual severity and symptom patterns, because there may be variable patterns of symptoms for similar severity values. Provide data on the age, position, and size of the specimens, which could further affect the utility of the SAD in some situations.
- When selecting raters for validation, make sure they do not have previous experience in using the SAD under evaluation. Provide standard instructions on how to recognize the symptoms of the disease and how to assess severity, first without and then with the SAD. It is not clear how many raters are required but we suggest a minimum of 15 raters selected randomly.
- Ideally repeat the assessment in time, with a 1- or 2-week interval, both without and with the aid, using the same set of raters in order to evaluate the effect of training and experience on gains in accuracy. One or more assessments could be made with a different set of randomly selected raters and the data analyzed separately to check consistency of the results obtained.
- Both pre- and posttest experiment conditions should be the same to avoid any impact of distraction on accuracy of estimates during the tests.
- To evaluate the effect of SAD on accuracy components, analyze the data, preferably using concordance analysis methods, to fully explore which component is affected and to gain insight into the ramification of errors. Linear regression should not be used as the sole method but it could be complementary for comparison with previous literature. Inferential methods should be used for testing hypotheses related to gain in accuracy and reliability. If parametric tests are used, make sure to check that the assumptions are not violated. Alternatively, nonparametric bootstrapping should be used when the conditions for parametric tests are not met. Reliability (intrarater or interrater) analysis should also be performed using concordance or intraclass correlation methods.
- When preparing the report, we encourage the use of reproducible research practices, including the availability of the raw data and the computer codes used for the analysis, which can be provided as supplementary materials and ideally hosted in a public repository.

In spite of the advances in digital image analysis and other methods of artificial remote sensing, visual assessment continues to be the most widely used method in phytopathometry (Bock et al. 2010) and is likely to remain important for many years. The surge in the development and evaluation of SAD during the early 2000s was likely fostered by the wide availability of cost-effective image analysis software and applicable statistical procedures but also reflects increasing recognition of their utility as an aid to obtaining more accurate data.

The SAD research reviewed in this study has fulfilled two valuable tasks: (i) the studies have provided useful tools to improve accuracy and reliability of severity estimates and (ii) they have begun to provide a fuller understanding of SAD technology and what aspects of SAD may be most beneficial to improve accuracy. For example, several studies, mainly conducted during the last 5 years, have explored how various factors related to SAD and the rater affect gains in accuracy. These include rater experience (Debona et al. 2015; González-Domínguez et al. 2014; Yadav et al. 2013), the software used for SAD design (Damasceno et al. 2014), the number of diagrams in a set (Bock et al. 2015; Braido et al. 2014a; Corrêa et al. 2009; Custódio et al. 2011), the color scheme (Angelotti et al. 2008; Buffara et al. 2014; Schwanck and Del Ponte 2014), characteristics of the incremental severity interval (Schwanck and Del Ponte 2014), and comparison between newly developed SAD and old SAD (Klosowski et al. 2013; Librelon et al. 2015).

Our review demonstrates that the field of SAD-based research remains active, with articles on SAD recently published more frequently in higher-impact journals in the discipline of plant pathology. However, to publish these articles as original research, particularly in high-impact journals, requires more than merely designing a SAD set and evaluating the impact on accuracy and reliability. The results from most studies demonstrate that SAD increase accuracy and reliability. Continued quantitative analysis of the gains from using SAD and the factors that affects their utility is needed, so that SAD can be designed to maximize the accuracy of severity estimates (Bock et al. 2016).

What aspects of a specific disease affect rater accuracy when using SAD (for example: symptom colors, lesion size, coalescence, lesion haloes, and lesion counts)? How many diagrams are optimal for different pathosystems and patterns of disease symptoms? What scale characteristics are best (linear, logarithmic, or a combination)? Does the software used to estimate actual severity have any effect on subsequent estimates? Should there be more illustrations at low severity because this is generally the most important range for severity estimation? Should diagram number and scale interval depend on the maximum severity observed in the pathosystem? Are there tendencies for raters to estimate "easy" values and can this tendency be reduced by improved SAD design? What is the minimum number of specimens required during validation? What is the minimum number of raters required during validation? Is this number related to innate ability or variability among raters? Are the gains from using SAD mostly in accuracy or precision, and does this depend on disease characteristics? These and other facets of SAD need to be addressed in the next phase of SAD research. Further exploration and consequent improvement in design will increase the value of this technology to improve accuracy of visual estimates. This review provides a synthesis of the current state of knowledge of SAD, and provides a basis for an outline of approaches and methods to employ when developing a new SAD. This is particularly important because even recently published studies have employed outdated (phase II or III) or incorrect concepts and poor methods. Based on our experience, analysis, and interpretation of these data, we propose a list of "best practices" when validating new SAD (Box 1).

SAD have been used for over 120 years and have demonstrably benefited the discipline of plant pathology and associated disciplines, including plant breeding. The majority of studies described herein have demonstrated the improvements in accuracy resulting from using SAD. However, we now need to base this on a better understanding of the impact of disease-related, environmental, rater, and SAD factors to determine whether there are approaches to SAD construction and validation that will further enhance the improvements in accuracy.

To facilitate access to the current knowledge on SAD technology and research, and to provide access to the data gathered in this study, we have developed a website (SADBank: http://emdelponte.github.io/sadbank/). The interactive dashboard allows for quick filtering and searching for SAD articles and data retrieved from the articles. SADBank will be updated continuously as more information or articles are published. We hope it will serve as a starting point for future work on the topic and a repository for raw data used in SAD research.

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