



# Streamlining leaf damage rating scales for the fall armyworm on maize

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## Abstract

The fall armyworm (*Spodoptera frugiperda*, Lepidoptera: Noctuidae), which is native to the Americas, has recently invaded Africa and Asia. There, it has become a major pest of maize (*Zea mays*). The variety of methods used to assess feeding damage caused by its caterpillars makes it difficult to compare studies. In this paper, we aim at determining which leaf damage rating scales for fall armyworm are most consistently used for which purposes, might provide most possibilities for statistical analyses, and would be an acceptable compromise between detail and workload. We first conducted a literature review and then validated the most common scales under field and laboratory conditions. Common leaf damage scales are the nominal “yes-no damage scale” that only assesses damage incidence, as well as difficult-to-analyse ordinal scales which combine incidence and severity information such as the “Simple 1 to 5 whole plant damage scale”, “Davis’ 0 to 9 whorl & furl damage scale”, or “Williams’ 0 to 9 whole plant damage scale”. These scales have been adapted many times, are sometimes used incorrectly, or were wrongly cited. We therefore propose simplifications of some of these scales as well as a novel “0.0 to 4.0 fall armyworm leaf damage index” which improves precision and possibilities for parametric data analyses. We argue that the choice of a scale to use should depend on the desired level of detail, type of data analyses envisioned, and manageable time investment.

**Keywords** *Spodoptera frugiperda* · Leaf damage rating scales · Damage index · Pest monitoring and decision-making

## Key message

- The fall armyworm is a maize pest in the Americas, Africa and Asia.

- Several methods are inconsistently used to assess the leaf damage it causes.
- We reviewed the literature and tested different leaf damage scales.
- Proposed scales in order of increasing detail and workload are:

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- Yes-No damage scale.
  - Simple 1–5 whole plant damage scale.
  - Davis' 0–9 whorl & furl damage scale
  - Williams' 0–9 whole plant damage scale.
  - Toepfer & Fallet 0.0–4.0 leaf damage index.
- Regressions allow comparisons among damage scales.

## Introduction

Damage scales are widely used to rate the impact of pests in agriculture, as well as to assess the efficacy of pest management measures. Unfortunately, it is often not easy to precisely quantify damage, for example a leaf area chewed by an insect or rotted by bacteria, or the decline in quality of produce, such as an apple with some, or many leaf spots of different sizes. Therefore, researchers and practitioners often apply scales of different types to rate damage (Velleman and Wilkinson 1993). However, this approach often leads to ordinal data which are difficult to analyse with parametric statistics (Stevens 1951). Other problems are unsure links between frequency and severity information (Blong 2003), nonlinear scale-damage relationships, and sometimes not accounting for the growth stage of a crop. This is particularly true for leaf feeders. For example, caterpillars of many lepidopteran pests of maize can attack leaves at different crop stages, some may also bore into tassels or cobs or stems, and others may destroy the vegetation growth point of the plant. Consequently, damage ratings become complicated and are often inconsistent (e.g. Ampofo 1986; Reddy et al. 2011; Eichenseer et al. 2008).

The fall armyworm (*Spodoptera frugiperda*, Lepidoptera: Noctuidae) is just such an intensively studied pest of maize, especially since its recent invasion of Africa and Asia from its origins in the Americas (Goergen et al. 2016; Ward and Kim 2019). The caterpillars of this *Spodoptera* species are considerably more voracious than many other noctuid maize pests (Day et al. 2017). Each of its six larval instars feeds extensively on young maize leaves often destroying the vegetation growth point of the plant. The caterpillars may also feed on tassels, silks and young maize cobs.

Since its detection in Africa in 2016 (Goergen et al. 2016), then a few years later in India (Ganiger et al. 2018) and finally in China (Ward and Kim 2019), it has become a major target of research (Li et al. 2019). Following its wide-spread invasion, about 190 papers have been published between 2016 and 2019, with regard to fall armyworm in Africa, and more than 350 papers in China in 2019 alone (Li et al. 2019). In total, more than 5000 articles have been published on fall armyworm between 1910 and 2019 (Li et al. 2019), covering all aspects ranging from diagnostics via life

history, invasion history and ecology, population genetics, to pest management and socio-economic impacts.

Some of these studies use the feeding damage caused by the caterpillars to assess, for instance, the spread of the species, the efficacy of pest management measures, or its economic impact. Growers and agricultural extension workers use ratings of damage symptoms as a way to monitor pest densities and then to take pest management decisions. However, there is a lack of consistency among the different proxies used to infer feeding damage caused by fall armyworm, leading to difficulties in making comparisons. For instance, some researchers only assess whether plants are damaged or not, leading to nominal data (Aguirre et al. 2019; FAO and CABI 2019). Others apply ordinal damage ratings (=ranks) from no damage up to heavy damage, or completely destroyed. The most used (but also misused) scale to estimate fall armyworm damage on maize plants is the so-called “Davis' 0 to 9 whorl & furl damage scale” (Davis et al. 1992). Assessment of the damage severity (i.e. intensity) and frequency (i.e. incidence) using this scale is only performed on the whorl & furl area of a plant, as this is where fall armyworm caterpillars mostly feed. In other cases, researchers assess the proportion and severity of damage of all leaves of a plant (Williams et al. 1989; Sisay et al. 2019a, b; Chinwada 2018). Again others prefer to assess cob damage instead of leaf damage, as this directly relates to yield loss (Prasanna et al. 2018; CIMMYT pers. comm.). Unfortunately, for many of these scales, the descriptive part of each score can be interpreted differently by different users, potentially leading to observer-biases during the rating process (Tversky and Kahneman 1974). Therefore, we would like to initiate a discussion on how to assess leaf feeding damage of the fall armyworm caterpillars in a less problematic and more comparable manner.

In this paper, we aim at determining which leaf damage rating scales for fall armyworm are most consistently used for which purposes, might provide most possibilities for statistical analyses, and would be an acceptable compromise between detail and workload. We first conducted a literature review and then validated the most common scales under field and laboratory conditions. This also allowed the establishment of relationships among scales, as well as to pest population densities. Taking the lessons learnt into account, we subsequently propose simplifications of some of the scales as well as a novel 0.0 to 4.0 fall armyworm leaf damage index which improves precision and possibilities for parametric data analyses. Our findings are intended to help researchers to more consistently use the damage scale that is best for their purpose, therefore allowing better compatibility and comparability among studies in the future.

## Material and methods

### Reviewing characteristics of damage rating scales

A literature review was conducted to assess which scales are most often and most consistently used to assess leaf damage of fall armyworm. We also tried to detect misinterpretations or incorrect uses of published scales in other studies, as well as advantages and disadvantages of the most-used scales (see criteria below).

We screened about 5000+ articles on fall armyworm for assessment methods of damage caused by this caterpillar to maize (Search term “fall armyworm” Or “*Spodoptera frugiperda*” in article title, 1910 to 2019, CAB Abstracts, Web of Knowledge; Scopus) (Li et al. 2019). More than 500 papers contained damage information (Search term “fall armyworm” Or “*Spodoptera frugiperda*” in title AND “damage” in abstract). The following papers contained detailed descriptions of damage scales: Wiseman et al. (1966); Williams et al. (1989); Ghidui and Drake (1989); Davis et al. (1992); Ayala et al. (2013); Zibanda et al. (2017); Chinwada (2018); Prasanna et al. (2018); Cruz and Turpin (1983); Figueiredo et al. (2006); dal Pogetto et al. (2012); Grijalba et al. (2018); Fotso Kuate et al. (2019); dos Santos et al. (2020). Of these, only the leaf damage rating scales were reviewed, and not the methods that were used to assess maize cob damage or caterpillar numbers.

Then, the most common scales, including a newly proposed one (see result section), were evaluated with regard to the following characteristics adapted from Bong (2003):

- **Clarity:** Is the scale easily understandable and not sensitive to differences in interpretation by the user?
- **Simplicity / distinctiveness:** Do the scale intervals describe classes of damage that can be easily distinguished?
- **Practicability:** Is the scale accurate enough at an acceptable level of workload, without the need for additional tools?
- **Validity / trustworthiness:** Are the scale and supporting data appropriately chosen with regard to damage patterns and behaviour of the pest?
- **Resolution:** Is the scale fine enough to allow meaningful interpretation of data?
- **Data quality:** Are the data sufficiently quantitative and can the data be used in parametric statistical inference ?
- **Robustness:** Do minor differences in plant damage not result in large differences in scale categories ?
- **Reliability/consistency:** Does use of the scale consistently produce the same result?
- **Spatial/temporal suitability:** Is the scale suitable at a range of spatial and temporal scales, i.e. for young and

older plants, for single plant trials as well as field scale trials?

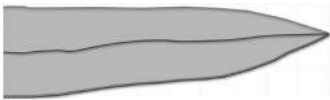




- **Applicability:** Is and can the scale be used internationally, nationally, locally; under different cropping systems, as well as in the field, semi-field, greenhouse, and laboratory?
- **Intuitively comprehensible result:** Does the final value on the scale have immediate recognition for users?
- **Decision utility:** Does the analysis provide a clear basis for action, i.e. are pest populations, damage and yield sufficiently correlated?

In addition, the scales analysed here (Tables 1, 2, 3, 4) were presented to and reviewed by about 100 maize experts from 21 countries at the 27th IOBC IWGO conference in 2019 (Toepfer et al. 2019).

### Field and laboratory validation

Five leaf damage scales were validated (i) under field conditions in five maize fields in Huye and Nyamagabe districts in southern Rwanda (two in November 2019, three in February 2020), as well as under standardised laboratory conditions with potted and caged plants in Switzerland in January 2020 (LD 12:12; 24 °C). Laboratory experimentation was added, as researchers not only face problems with assessing caterpillar damage in the field, but also in the laboratory,

**Table 1** Simple 1 to 5 damage scale for the fall armyworm. Usually used as a whole plant assessment, but adaptable to a whorl & furf assessment

Score	Simple 1 to 5 whole plant damage scale for the fall armyworm (whole plant assessed)	
1	No damage	
2	Little damage	
3	Medium damage	
4	Heavy damage (most of the plant with damage symptoms)	
5	Very heavy or total damage (plant is almost dying)	

Usually used for pest monitoring and decision-making

**Table 2** Original and simplified Davis' 0 to 9 whorl & furl damage scale for the fall armyworm as a quick top-view visual assessment of a maize plant

Score	Original and simplified Davis' 0 to 9 whorl & furl damage scale for the fall armyworm (leaf whorl & furl assessed)	14-day rating (Davis et al. 1992)	Simplified day-independent rating
0	No visible damage	No visible damage	No visible damage
1	Only pinhole lesions present on whorl leaves	Only pinhole lesions present on whorl leaves	Only pinholes on whorl leaves
2	Pinholes and small circular lesions present on whorl leaves	Pinholes and small circular lesions present on whorl leaves	Pinholes and small circular lesions on whorl leaves
3	Pinholes, small circular lesions and a few small elongated (rectangular shaped) lesions of up to 1.3 cm (1/2") in length present on whorl and furl leaves	Small circular lesions and a few small elongated (rectangular shaped) lesions of up to 1.3 cm (1/2") in length present on whorl and furl leaves	Pinholes, small circular lesions and a few small < 1.3 cm (< 1/2") elongated lesions on whorl and/or furl leaves
4	Small elongated lesions present on whorl leaves and a few mid-sized elongated lesions of 1.3 to 2.5 cm (1/2—1") in length on whorl and/or furl leaves	Several small to mid-sized 1.3 to 2.5 cm (1/2—1") in length elongated lesions present on a few whorl and furl leaves	Small elongated and a few mid-sized 1.3—2.5 cm (1/2—1") elongated lesions on whorl and/or furl leaves
5	Small elongated lesions and several mid-sized elongated lesions present on whorl and furl leaves	Several large elongated lesions greater than 2.5 cm (1") in length present on a few whorl and furl leaves and/or a few small-to mid-sized uniform to irregular shaped holes (basement membrane consumed) eaten from the whorl and/or furl leaves <sup>a</sup>	Small elongated and several mid-sized 1.3—2.5 cm (1/2—1") elongated lesions on whorl and/or furl leaves
6	Small and mid-sized elongated lesions plus a few large elongated lesions of greater than 2.5 cm (1") in length present on whorl and/or furl leaves	Several large elongated lesions present on several whorl and furl leaves and/or several large uniform to irregular shaped holes eaten from furl and whorl leaves <sup>a</sup>	Small and mid-sized elongated lesions plus a few large > 2.5 cm (> 1") elongated lesions on whorl and/or furl leaves
7	Many small and mid-sized elongated lesions present on whorl leaves plus several large elongated lesions present on the furl leaves	Many elongated lesions of all sizes present on several whorl and furl leaves plus several large uniform to irregular shaped holes eaten from the whorl and furl leaves	Many small and mid-sized elongated lesions plus several large > 2.5 cm (> 1") elongated lesions on whorl and furl leaves
8	Many small and mid-sized elongated lesions present on whorl leaves plus many large elongated lesions present on the furl leaves	Many elongated lesions of all sizes present on most whorl and furl leaves plus many mid- to large-sized uniform to irregular shaped holes eaten from the whorl and furl leaves	Many small and mid-sized elongated lesions on whorl leaves plus many large > 2.5 cm (1") elongated lesions on whorl and furl leaves
9	Many elongated lesions of all sizes on most whorl and furl leaves plus a few uniform to irregular shaped holes (basement membrane consumed) eaten from the base of whorl and/or furl leaves	Whorl and furl leaves almost totally destroyed	Whorl and furl leaves almost totally destroyed

7-day and 14-day rating scale only for mid-whorl stage maize artificially infested with neonate fall armyworms and originally developed for maize resistance studies (Davis et al. 1992). The simplified scale can be used at any vegetative maize growth stage and is independent from larval instar. The scales are used for research purposes, including efficacy evaluations of treatments

<sup>a</sup>Scores 5 and 6 to adjust for feeding damage caused by migratory mid-instar larvae. Plants that have feeding by migratory larvae exhibit a break in the sequence of types of larval feeding lesions (Davis et al. 1992)

particularly when maize may grow slimmer and less strong than under field conditions.

Artificial infestation with three third instar caterpillars per plant was used in the two fields of 2019 based on 60 potted maize plants placed into each field, and in the laboratory in 2020 using two potted maize plants per each of 15 sleeve cages. Natural infestation was used in farmer fields in 2020. Rwandan maize grain hybrids were used in all experiments.

Each scale was used to assess the damage on 60 to 80 individual plants per experiment, and this at three intervals of five days in 2019, as well as once in January and once in February 2020. The number of caterpillars per plant were also recorded when making each damage assessment. The assessments covered the maize growth stages from 4 to 14 leaves. The assessments were individually done by three researchers and two technical assistants, regularly switching the person's responsibility for one of the scales.

Regressions were applied to estimate how scores of the damage grade corresponded to each other, as well as to the pest's population density of caterpillars (Kinnear and Gray 2000) (Figs. 1, 2, 3).

Moreover, the time needed for assessment of each plant was recorded. Univariate GLM was used to analyse the influence of damage level, i.e. the damage score values and plant size on the time needed to carry out an assessment.

## Results

### Characteristics of fall armyworm damage rating scales

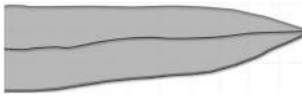
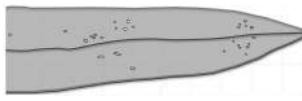
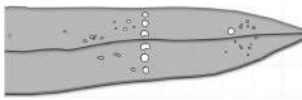
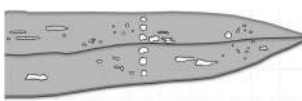
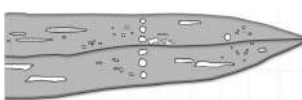
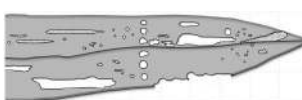
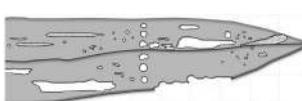



Our review revealed that four scales are most widely applied to visually assess leaf damage of fall armyworm caterpillars on maize plants. They can be ranked in the following order of increasing detail and workload: (1) the nominal “yes-no damage scale” (Gómez et al. 2013; De La Rosa-Cancino et al. 2016; Zibanda et al. 2017; Midega et al. 2018; Aguirre et al. 2019; FAO and CABI 2019; Jaramillo-Barrios et al. 2019; Maruthadurai and Ramesh 2020) (Table 1), the ordinal scales (2) “Simple 1 to 5 whole plant damage scale” (Cruz and Turpin 1983; Figueiredo et al. 2006; dal Pogetto et al. 2012; Grijalba et al. 2018; Fotso Kuate et al. 2019; dos Santos et al. 2020), (3) “Davis’ 0 to 9 whorl & furl damage scale” (Davis et al. 1992) (Table 2), and (4) “Williams’ whole plant 0 to 9 leaf damage scale for fall armyworm” (Williams et al. 1989) (Table 3). As the latter two originally only consider assessments after artificial infestation with neonates, and as both scales had been widely adapted and occasionally used incorrectly, we propose simplified scales for both (see below and Tables 2, 3).

The existing scales all provide nominal or ordinal (rank) data types, but are not always compatible and sufficiently informative. They are also difficult to be analysed with parametric statistics. We therefore created a novel 0.0 to 4.0 leaf damage index allowing finer, more linear, and more accurate assessments (see below and Table 4).

The “*yes–no damage scale*” records whether a maize plant is damaged by the fall armyworm, independent of damage severity (Gómez et al. 2013; De La Rosa-Cancino et al. 2016; Zibanda et al. 2017; Midega et al. 2018; Aguirre et al. 2019; FAO and CABI 2019; Jaramillo-Barrios et al. 2019; Maruthadurai and Ramesh 2020). It is a rough estimate of fall armyworm presence in a certain area and widely used for pest monitoring and decision-making. The advantage of the scale is that (a) it is less labour and time intensive than other scales, (b) it can be applied to all maize growth stages, including tasselling or ripening, and (c) it reflects the fall armyworm population density relatively well because usually only one caterpillar is found per plant (except for neonates that can be numerous) (Fig. 1). A disadvantage is that it does not provide information on the severity of damage. Moreover, its nominal data type is statistically problematic at low sample sizes (Blong 2003). Therefore, depending on the variation in infestation in the experimental area, 20 but often up to 50 plants are usually examined to allow the calculation of reliable percent damage (Dent and Walton 1998). Consequently, frequency analyses are applied. Moreover, as long as there are not too many 0 and 100% values, percent damage can be considered quasi-interval data type, therefore allowing parametric statistical analyses. Otherwise, binomial GLMs and logistic regression will have to be used.

The “*simple 1 to 5 whole plant damage scale for fall armyworm*” (Table 1) is the most used among the 5-category scales (1 to 5 or 0 to 4 scales; Cruz and Turpin 1983; Figueiredo et al. 2006; dal Pogetto et al. 2012; Grijalba et al. 2018; Fotso Kuate et al. 2019; dos Santos et al. 2020). It allows a rough, quick assessment of frequency and severity of leaf damage. It can be used for pest monitoring and decision-making in armyworm management. The scale usually only considers the plant as a whole and not each leaf separately. However, it can also be used to study short-term treatment effects by only assessing the whorl and furl area of a plant. The scale is of the ordinal data type, resulting in a damage ranking. The advantages of this scale are that (a) it is less labour and time intensive than most other scales, and (b) it can be applied to all maize growth stages, including tasselling or ripening (Table 5). The disadvantages are that (a) fine differences between damage levels cannot be distinguished, and (b) human bias may influence the results due to different judgements on what little, medium or heavy mean with regard to damage. Median and percentiles are calculated rather than arithmetic means. However, its ordinal

**Table 3** Original and simplified Williams' 0 to 9 whole plant leaf damage scale for the fall armyworm

Score	Original and simplified Williams' 0 to 9 whole plant leaf damage scale for the fall armyworm (whole plant assessed)		
	14-day rating (Williams et al. 1989)	Simplified day-independent rating	
0	No visible damage to leaves	No damage	
1	Only pinhole lesions on whorl leaves	Pinhole damage on few leaves	
2	Pinhole and shot-hole lesions on whorl leaves	Small circular hole- or window pane-feeding and/or shot-hole damage on less than 1/3 of leaves	
3	A few small (0.5–1 cm) elongated lesions on leaves	< 1 cm elongated holes or window panes on less than 1/3 of leaves	
4	Several leaves with mid-sized (1–3 cm) lesions	1–3 cm elongated holes and/or window panes > 1 cm on less than 1/3 of leaves. Or not more than one > 3 cm hole	
5	Several leaves with large elongated lesions or small portions eaten away	Some > 3 cm elongated and some smaller holes on less than 1/3 of leaves	
6	Several leaves with elongated lesions and large portions eaten away	Some > 3 cm elongated and many smaller holes on about 1/2 of leaves	
7	Many elongated lesions and large portions eaten from leaves	Many holes of all sizes and shapes on about 1/2 of leaves	
8	Many elongated lesions and many large portions eaten from leaves	Many holes of all sizes and shapes on most leaves	
9	Many leaves destroyed	Most leaves almost totally destroyed and/or vegetation point destroyed	

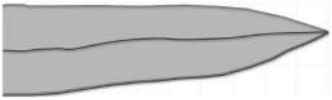

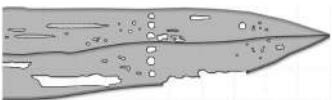


As a whole plant assessment, the Williams' scale is usually used for 14-day assessments after artificial infestation with neonate fall armyworms (Williams et al. 1989). The simplified scale can be used for any instar and infestation. The scales are used for research purposes, including maize hybrid evaluations

data type may prevent applying certain parametric statistical inference methods (Blong 2003).

The “Davis' 0 to 9 whorl & furl damage scale for fall armyworm” (Table 2) (Davis et al. 1992) is of the ordinal data type, and ranks damage in combination with frequency and severity information. It is historically and currently the most used leaf damage scale for the fall armyworm (Wiseman et al. 1996; Davis et al. 1996; Williams et al. 1999; Lynch et al. 1999a, 1999b; Rea et al. 2000, 2002; Buntin et al. 2001, 2004, Buntin 2008; Michelotto et al. 2017; Lourenço et al. 2017; Sisay et al. 2019a; Vassallo et al. 2019; Nboyine et al. 2020; Teixeira Silva et al. 2020). It has been

particularly used to assess resistance levels of maize hybrids to fall armyworm feeding. Originally, two such scales were developed (Davis et al. 1992), one for a 7-day and one for a 14-day assessment after artificial infestation with neonates (Table 2). The 7-day assessment has been more frequently used, often for any instar, whereas it was originally developed to assess damage caused by one-week old caterpillars only. Here, we combined the two scales (7- and 14-day assessment) into one that allows assessments at any instar, and we simplified the descriptive part of each damage level to facilitate the distinction between these levels (Table 2). The Davis scale is exclusively used for a quick top-view

**Table 4** Novel 0.0 to 4.0 fall armyworm leaf damage index

Score	0.0 to 4.0 fall armyworm leaf damage index (each leaf assessed)	
0	No damage	
1	Little damage (pinholes, and/or small holes, small leaf edge parts eaten, shot holes)	
2	Medium damage (some larger holes and/or larger leaf edge areas eaten)	
3	Heavy damage (many larger holes and/or larger leaf edge areas eaten)	
4	Total damage (destroyed, non-functional leaves) <sup>a</sup>	
0.00 to 4.00	Average score after summing up all scores from each leaf and dividing by the number of assessed leaves	

Leaves are individually assessed for damage, summed up and then divided by the total number of assessed leaves. Some lower leaves may not be assessed if they have dried out. This scale is used for research purposes including treatment efficacy trials

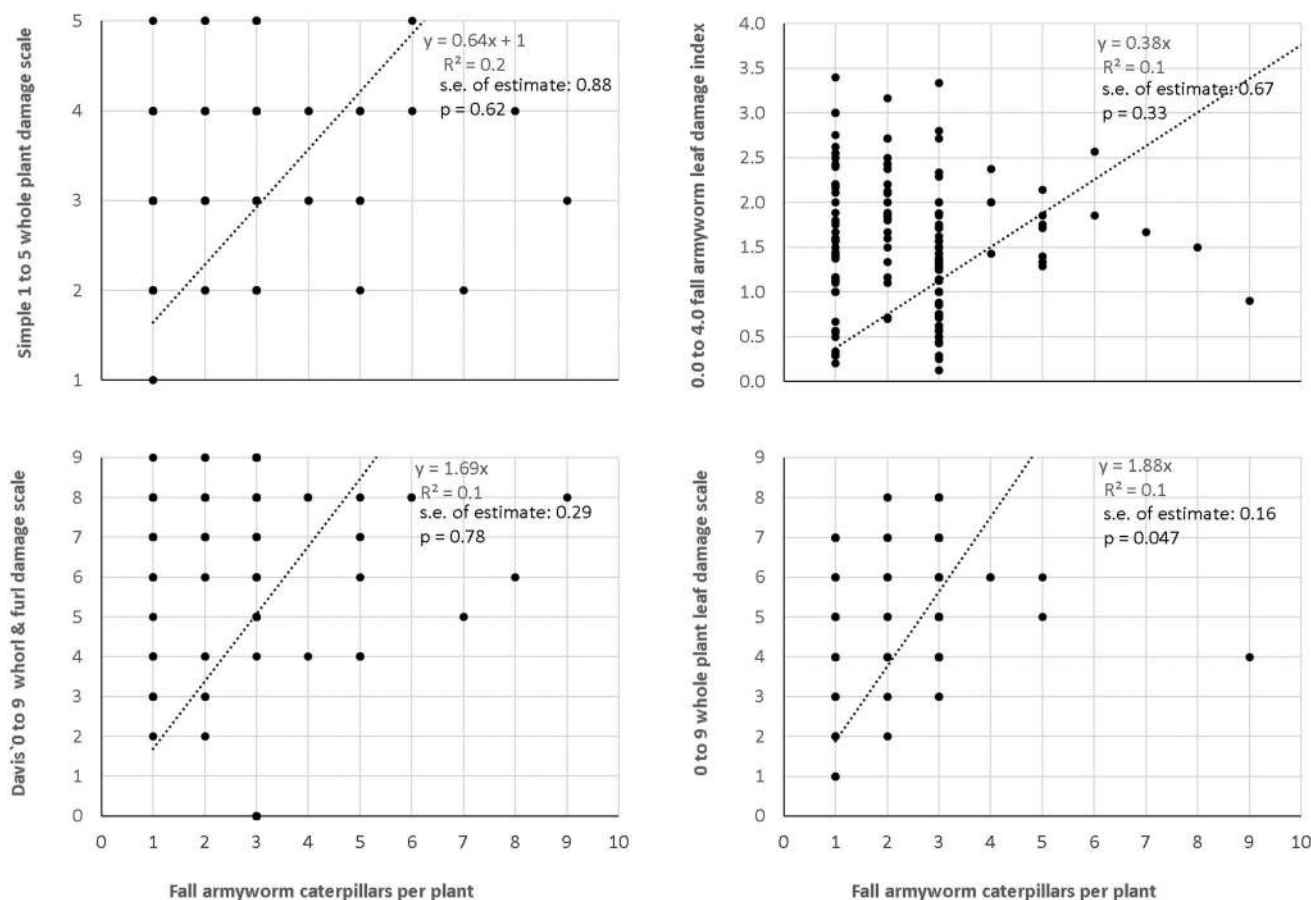
<sup>a</sup>Alternatively, score 4 if the vegetation point or tassel or cob of maize is damaged

visual assessment of damage to the leaf whorl and the furl area, because the fall armyworm caterpillar almost exclusively feeds on the leaves inside the whorl. This implies that the scale only assesses recent damage, and not previous damage usually found on older, lower leaves.

Median and percentiles are calculated rather than arithmetic means. The advantage of the scale is that (a) it is a good compromise between detail and labour intensity, (b) relatively fine differences in damage levels can be assessed, (c) it mainly considers recent damage, thus allowing assessment of recent treatment effects, and (d) many studies have used this scale (Table 5). The disadvantages are that (a) human bias may influence the results due to its rather complicated, non-consistently explained rating levels across the scores and therefore differently interpretable descriptive parts, particularly between scores 5 and 7, (b) the scale is made for whorl leaf stages, thus vegetative growth stages only, (c) it only assesses the most recent damage, although this can be an advantage when assessing treatment effects; but is less suitable for longer assessment periods such as for maize tolerance or resistance, (d) it is of the nonlinear, ordinal data type limiting the use of parametric statistical inference (Blong 2003), and finally (e) researchers tend to frequently adapt and change the scale for their own purposes (Chinwada 2018; Prasanna et al. 2018), such as changing it from a 0–9 to a 1–9 scale (Ni et al. 2008; Aguirre et al. 2019; Baudron et al. 2019; Sisay et al. 2019b, a) or using the scale

for whole plant assessment (Sisay et al. 2019b). This leads to misinterpretations when comparing studies, something we try to resolve by proposing a simplified instar-independent scale (Table 2).

The “Williams’ whole plant 0 to 9 leaf damage scale for the fall armyworm” (Table 3) (Williams et al. 1989) assesses the frequency and severity of damage across the whole plant, leading to a more comprehensive estimation of plant damage than the Davis scale used for the whorl and furl area only. It is about half as often cited as the Davis scale (e.g. in Williams and Buckley 2008; Phambala et al. 2020). It has been mostly used in maize hybrid trials as a 14-day assessment after artificial infestation with neonates. Here, we combined Williams’ scale and the whole plant Davis’ scale adaptations (Sisay et al. 2019b) into one whole plant assessment scale, and simplified the descriptive part of each damage level, to facilitate the distinction between levels (Table 3). Median and percentiles are calculated rather than arithmetic means. The advantages of this scale are that (a) relatively fine differences in damage levels can be assessed and (b) its descriptive part attempts a quantitative assessment by providing the proportion of damaged leaves of an entire plant, (c) it includes old and recent damage, and (d) it can be applied to young and older plants (Table 5). The disadvantages are that (a) it is time consuming, (b) the scale is made for vegetative growth stages only, and (c) it is of nonlinear, ordinal data type limiting some parametric statistical inference (Blong



**Fig. 1** Relations between the numbers of fall armyworm caterpillars on maize plants and damage, assessed through different leaf damage scales. Data from three naturally infested fields of vegetative-stage

maize in southern Rwanda. Linear regression models plotted with adjusted  $R^2$  and standard errors (SE) of estimates. Univariate GLMs'  $p$  values shown

2003), and (d) researchers tend to frequently adapt and change the scale to their purposes. This leads to misinterpretations when comparing studies, which we try to resolve here by proposing a simplified instar-independent scale (Table 3).

The novel “0.0 to 4.0 fall armyworm leaf damage index” is a fine-resolution damage assessment that combines severity and frequency information (Table 4). It is designed for research trials, particularly for assessments of treatment effects on the fall armyworm and its damage.

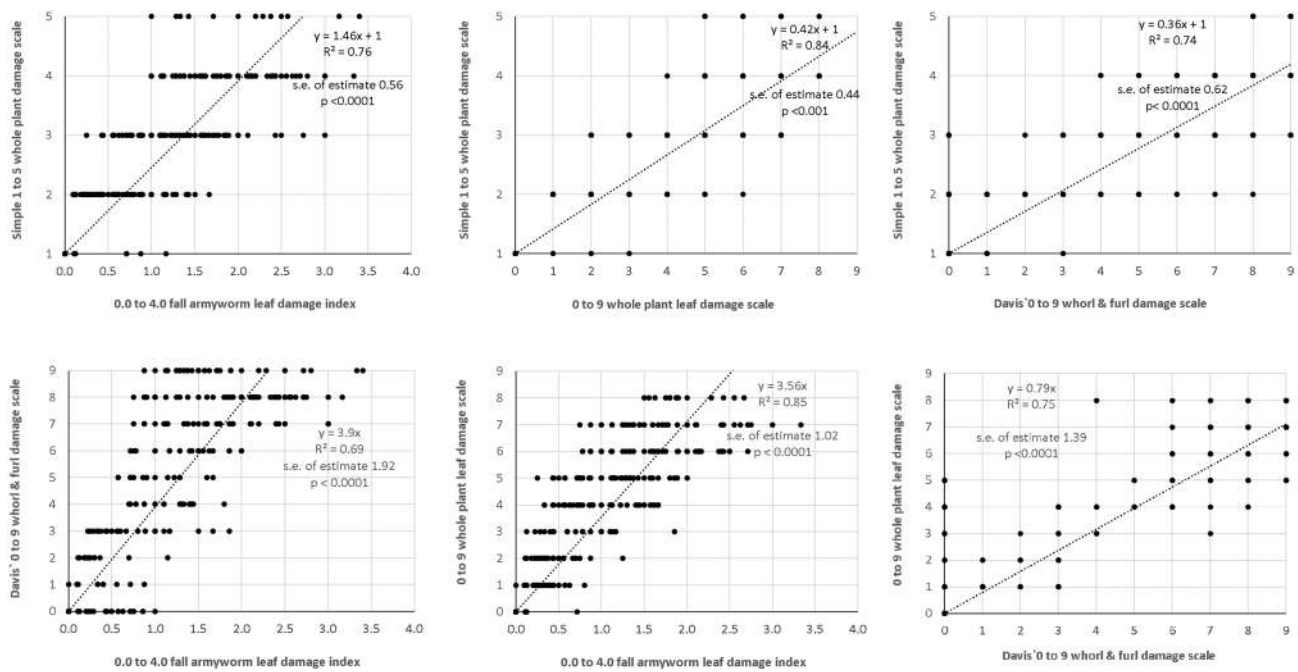
Each leaf is assessed individually for damage, and the scores of each leaf are summed up and divided by the total number of assessed leaves. The minimum index for an entire plant is 0.0 (i.e. no damage), and the maximum index is 4.0 (i.e. total damage). When first, second or third leaves of older and larger plants have dried out (senesced), they are not assessed and not included in the calculation. The obtained index is of ratio data type, which comes close to continuous, linear data (i.e. it is only ordinal at the leaf rating step, but then standardised to the total number of leaves). The advantages of this scale are that (a) fine differences in damage levels can be assessed, which can be useful if

precise research results are required, (b) it can be similarly applied to small, young and larger, older plants, and most importantly, and (c) the obtained ratio data allow calculations of means, standard deviations, coefficients of variation, and the application of parametric statistics as for interval data types (Blong 2003) (Table 5). The disadvantages are that (a) this scale is labour intensive in terms of assessment as well as data entry and (b) the scale is suitable for vegetative growth stages only.

### Relationships between fall armyworm damage rating and caterpillar populations

None of the leaf damage rating scales are suitable for predicting densities of populations of fall armyworm caterpillars in the field (see low  $R^2$  values, and  $p$  values in Fig. 1). One reason is that neonates and young caterpillars are often found in larger numbers per plant; but only one larger older caterpillar usually inhabits a single plant. Moreover, several





**Fig. 2** Relations between scales of leaf damage caused by fall armyworm caterpillars. Data from fields with natural fall armyworm infestations of vegetative-stage maize in southern Rwanda (two locations in 2019, three locations in 2020), and from artificially infested maize

plants in two laboratory experiments. Linear regression models plotted with adjusted  $R^2$  and standard errors (SE) of estimates. Univariate GLMs'  $p$  values shown

## Relationships among fall armyworm damage rating scales

tiny caterpillars cause relatively little damage, whereas a single large caterpillar can heavily damage a plant. The trendlines in Figs. 2 and 3 reflect how scores relate from one damage scale to another. The “Simple 1 to 5 whole plant damage scale”, “Davis' 0 to 9 whorl & furl damage scale”, “Williams' 0 to 9 whole plant leaf damage scale” and the “0.0 to 4.0 fall armyworm leaf damage index” appeared relatively well associated among each other (Fig. 2). Those indicate that comparisons among studies and with previous research might be possible. The scales based on whole plant assessments are slightly more comparable to each other than to the scales based on whorl and furl assessments. Variability appears particularly high at low and high damage levels (for example see variability pattern when relating the Davis' scale to other scales).

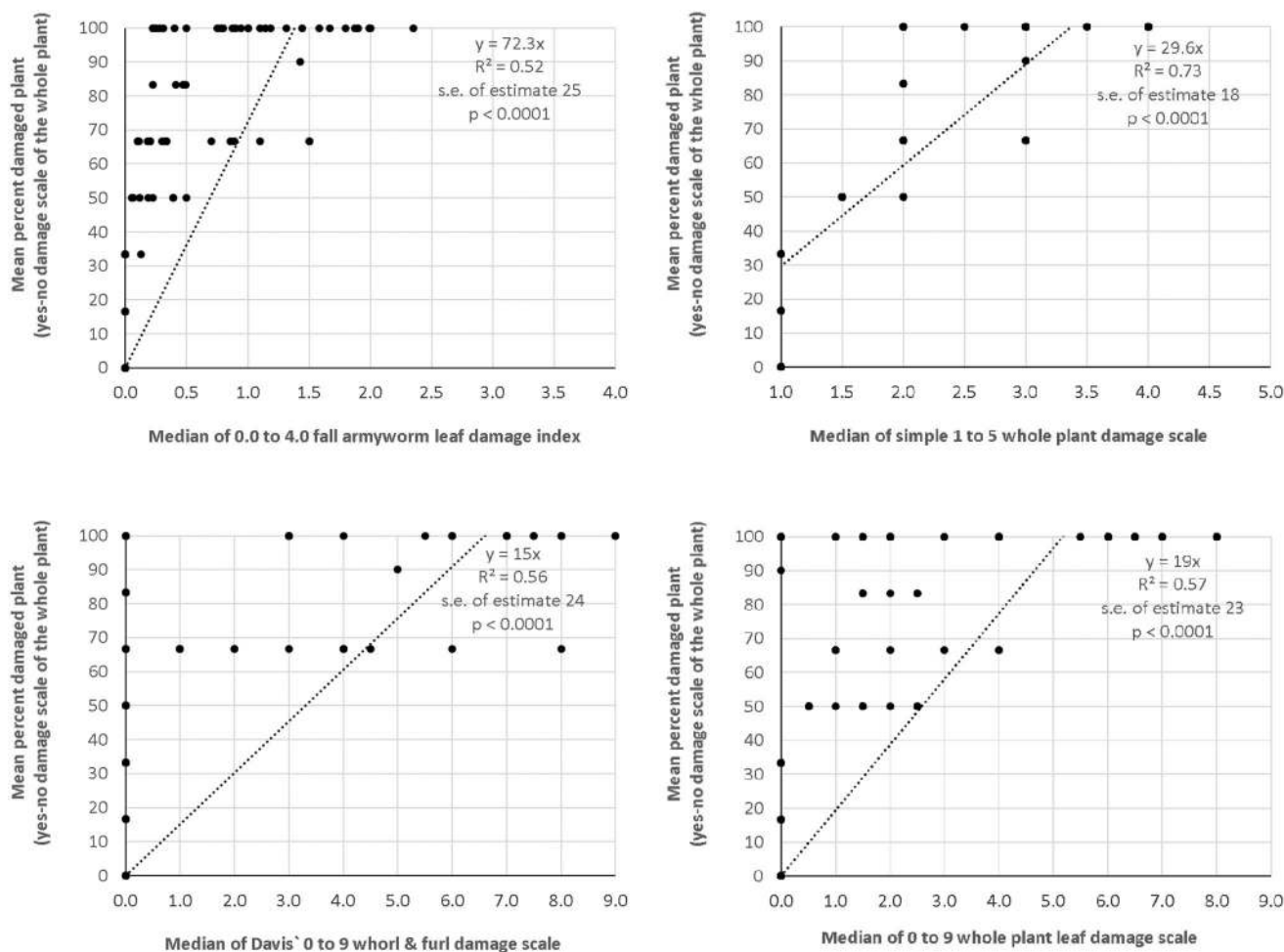
As for the “yes–no damage scale”, only averages of larger sets of assessed plants can be associated with the other damage scales. Relationships were, as expected, poor (see larger standard errors of estimates in Fig. 3). To some extent, small and medium damage as per 1 to 5 whole plant damage scale could be related to percentages of damaged plants. However, the more damage, the poorer the relationship. The reason is

that even one single caterpillar can cause heavy or even total damage, particularly the older caterpillars on younger plants.

## Relationships between efforts of time in damage assessments and detail

Different leaf damage scales provide different levels of detail in the following order from the least detailed “yes–no damage scale” (2 intervals of detail) via the “Simple 1 to 5 whole plant damage scale” (5 intervals), the “Davis' 0 to 9 whorl & furl damage scale” (9), the “Williams' 0 to 9 whole plant leaf damage scale” (9) up to the most detailed “0.0 to 4.0 fall armyworm leaf damage index” with, for example, 20 intervals of detail at 4 leaf stage and 60 levels of detail at 12 leaf stage coming close to true interval data.

The scales required different investments of time for damage assessment (GLM,  $F_{4;126} = 29$ ;  $p < 0.0001$ ). The fastest damage assessments were possible when using the “yes–no damage scale” and the “Simple 1 to 5 whole plant damage scale”, requiring  $2.5 \pm 2.2$  and  $2.6 \pm 0.9$  s per plant, respectively (Fig. 4). About double the time was needed for the “Davis' 0 to 9 whorl & furl damage scale” ( $4.8 \pm 2.4$  s), and about three times the time for the “Williams' 0 to 9 whole plant leaf damage scale” ( $6.9 \pm 4.5$  s). In general, more time was usually needed to assess medium damage than light or heavy damage (see curves in Fig. 4). In contrast, the “Simple 1 to 5 whole



**Fig. 3** Relations between percent damage in experimental plots and the medians of leaf damage scales from the same plots. Data from natural fall armyworm infestations of vegetative-stage maize in southern Rwanda (two locations in 2019, three locations in 2020), and

from artificially infested maize plants in two laboratory experiments. Linear regression models plotted with adjusted  $R^2$  and standard errors (SE) of estimates. Univariate GLMs'  $p$  values shown

plant damage scale" was the only scale where the amount of damage did not influence time needed for assessment (see  $p$  values in Fig. 4).

The most detailed scale, the "0.0 to 4.0 fall armyworm leaf damage index" was also the most labour-intensive scale requiring about  $12.6 \pm 6.5$  s per plant. Assessment time increased with increasing damage across leaves as well as with the size of the maize plant, reflected by its number of leaves ( $p = 0.046$ ). In contrast, leaf numbers had no detectable influence on the time needed to assess damage via the "yes–no damage scale" ( $p = 0.51$ ), the "Simple 1 to 5 whole plant damage scale" ( $p = 0.58$ ), the "Williams' 0 to 9 whole plant leaf damage scale" ( $p = 0.89$ ), and logically not via the "Davis' 0 to 9 whorl & furl damage scale" as only the upper 3 to 4 leaves are assessed for the latter independent of plant size.

## Discussion

Our review of over 500 scientific publications related to fall armyworm damage revealed that four scales are most widely applied. They are the nominal "yes–no damage scale" (Gómez et al. 2013; De La Rosa-Cancino et al. 2016; Zibanda et al. 2017; Midega et al. 2018; Aguirre et al. 2019; FAO and CABI 2019; Jaramillo-Barrios et al. 2019; Maruthadurai and Ramesh 2020), the ordinal "Simple 1 to 5 whole plant damage scale" (Cruz and Turpin 1983; Figueiredo et al. 2006; dal Pogetto et al. 2012; Grijalba et al. 2018; Fotso Kuate et al. 2019; dos Santos et al. 2020), "Davis' 0 to 9 whorl & furl damage scale" (Davis et al. 1992), and "Williams' whole plant 0 to 9 leaf damage scale for fall armyworm" (Williams et al. 1989). As those scales all provide difficult-to-analyse nominal or ordinal (rank) data types, we created a novel 0.0 to 4.0 leaf damage index allowing finer, more linear, and therefore more accurate assessments. Then,

**Table 5** Suggested comparison of leaf damage rating scales used for assessing damage by fall armyworm caterpillars

Characteristics	Yes-No damage scale of the whole plant	Simple 1 to 5 whole plant damage scale	Davis' 0 to 9 whorl & furl damage scale	Williams' whole plant 0 to 9 leaf damage scale	Toepfer & Fallet 0.0 to 4.0 fall armyworm leaf damage index
Clarity	☺	☹	☹	☹	☹
Simplicity/ distinctiveness	☺	☹	☹	☹	☹
Practicability / workload <sup>a</sup>	☺	☹	☹	☹	☹
Validity / trustworthiness	☹	☺	☺	☺	☺
Resolution <sup>b</sup>	☹	☹	☺	☺	☺
Data quality	☹ Nominal	☹ Ordinal	☹ Ordinal	☹ Ordinal	☺ Ratio
Robustness	☺	☺	☹	☹	☺
Reliability/consistency	☺	☹	☹	☺	☺
Spatial/temporal suitability	☺	☺	☹	☹	☹
Applicability	☺	☺	☹	☹	☺
Intuitively comprehensible result	☺	☺	☺	☺	☺
Reflecting pest population <sup>c</sup>	☹	☹	☹	☹	☹
Decision utility	☹	☺	☺	☺	☺
Assessing treatment effects	☹	☹	☺ <sup>d</sup>	☹	☹

☺ advantageous, ☹ disadvantageous, ☹ intermediate

<sup>a</sup>Time needed to assess damage on per plant are on average 2.5, 2.6, 4.8, 6.9, 12.6 s, respectively for the scales

<sup>b</sup>Details levels are 2, 5, 9, 9, and many close to interval data, respectively for the scales

<sup>c</sup>R2 values of regressions between scales and caterpillar population: NA, 0.2, 0.1, 0.1, 0.1, respectively for the scales

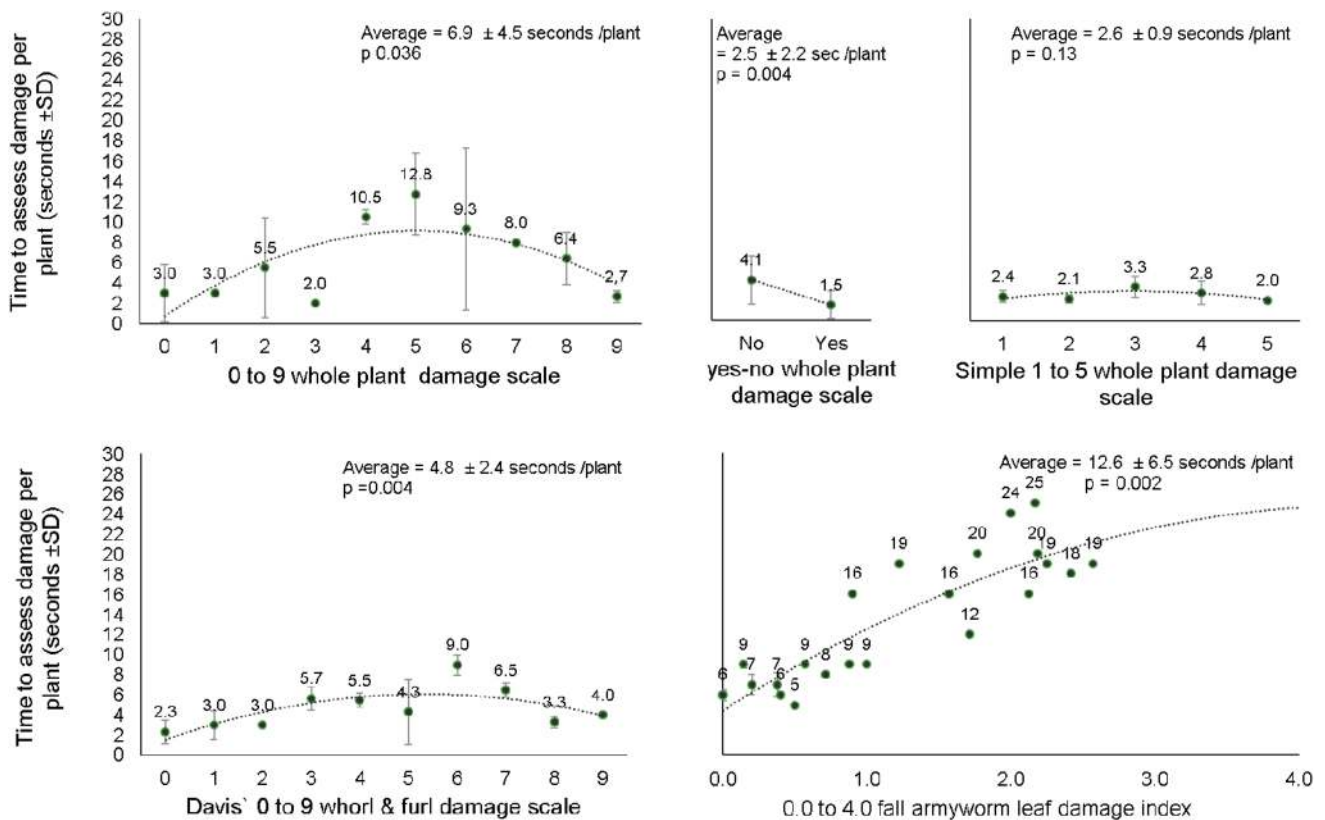
<sup>d</sup>The only scale that only assesses recent damage

*Clarity* – is the scale easily understandable and not sensitive to differences in interpretation by the user? *Simplicity / distinctiveness*– do the scale intervals describe classes of damage that can be easily distinguished? *Practicability* – is the scale accurate enough at an acceptable level of workload, without the need for additional tools? *Validity / trustworthiness*– are the scale and supporting data appropriately chosen with regard to damage patterns and behaviour of the pest? *Resolution* – is the scale fine enough to allow meaningful interpretation of data? *Data quality* – are the data sufficiently quantitative and can the data be used in parametric statistical interference? *Robustness*– do minor differences in plant damage not result in large differences in scale categories? *Reliability / consistency* – does use of the scale consistently produce the same result? *Spatial / temporal suitability*—is the scale suitable at a range of spatial and temporal scales, i.e. for young and older plants, for single plant trials as well as field scale trials? *Applicability* – is and can the scale be used internationally, nationally, locally; under different cropping systems, as well as in the field, semi-field, greenhouse, and laboratory? *Intuitively comprehensible result* – does the final value on the scale have immediate recognition for users? *Decision utility* – does the analysis provide a clear basis for action, i.e. are pest populations, damage and yield sufficiently correlated?

we successfully tested and validated those scales in comparison with each other under field and laboratory conditions at different maize growth stages and different pest populations.

A number of other damage rating scales exist in the literature. For example, there is a 0 to 5 leaf %-damage scale (0 = no damage, 1 = slight damage (pinholes), 2 = moderate

damage (10 to 25% of leaves or whorl damaged), 3 = heavy damage (25 to 50% of leaves or whorl damaged), 4 = severe damage (50 to 75% of leaves or whorl damaged), 5 = entire whorl destroyed) (Ghidiu and Drake 1989), and another 1 to 5 leaf damage scale (1 = No evident damage, or less than 1–3 pinhole type injuries; 2 = More than 3 pinhole



**Fig. 4** Time needed to assess different levels of leaf damage caused by the fall armyworm caterpillars to maize plants using different leaf damage scales. Polynomial regression lines plotted. Univariate GLM applied and  $p$  values show for influence of scores on time

type injuries, and/or 1–3 injuries less than 10 mm each; 3=More than 3 injuries less than 10 mm, and/or 1–3 injuries larger than 10 mm each (shot-hole-type injuries); 4=3 to 6 shot-hole-type injuries, and/or at least 50% of the whorl destroyed; 5=More than 6 shot-hole-type injuries, and/or whorl totally destroyed) (Ayala et al. 2013). There is also a 0 to 10 leaf damage scale used for damage assessments of maize under greenhouse conditions (0=no visible damage; 1=small amount of pinhole type injury; 2=several pinholes; 3=small amount of shot-hole type injury with 1 or 2 lesions; 4=several shot-hole type injuries and few lesions; 5=several lesions; 6=several lesions, shot-hole injury and portions eaten away; 7=several lesions and portions eaten away with some areas dying; 8=several portions eaten away and areas dying; 9=the whorl almost or completely eaten away and several lesions with more areas dying; 10=plant dead, dying or almost completely destroyed (Wiseman et al. 1966)). However, all those scales are less frequently used, and some are in their descriptive parts slightly inconsistent.

Moreover, regardless of which damage rating scale is used for the fall armyworm, it needs to be emphasized that the caterpillars still need to be identified (Toepfer 2017;

FAO and CABI 2019). This is, because armyworms, corn borers, stalk/stem borers and other caterpillars of lepidopteran pests can cause similar damage symptoms. This is the case for pinholes, shot holes, window panes, and elongated feeding holes in leaves. Some major differences resulting from fall armyworm feeding compared to other caterpillars' damage are (a) the extensiveness of feeding seen as large ragged feeding holes, large parts of the leaf edges eaten, and an often completely destroyed vegetation growth point, (b) the large amount of frass in the whorl and furl, and (c) that fall armyworm caterpillars rarely enter the maize stems and thus rarely leave bore holes and broken stems (FAO and CABI 2019).

Our review, analyses and validation of the most commonly used damage scales of the fall armyworm and the novel damage index confirmed problems of a general nature relevant to many damage scales. First, scales are compromises between the need for detailed information and being simple enough for practical use. The scales studied here can be ranked in an order of increasing detail and workload (Table 5). Second, most rating scales are hybrid scales combining frequency and severity information. The unsure link

between these two types of information is a common problem with many damage assessment data (Blong 2003). In our study, only the “Williams’ 0 to 9 whole plant leaf damage scale” and the “0.0 to 4.0 leaf damage index” account for this problem. Third, damage scales may be of nominal, ordinal (rank), interval or ratio data type (Stevens 1946; Blong 2003). Although these data concepts have been criticized for their simplicity (Velleman and Wilkinson 1993), they remain frequently related to requirements for statistical tests. Unfortunately, most pest damage scales, including the ones studied here, generate ordinal data that are difficult to analyse. In fact, statistical analyses involving means and standard deviations should be avoided here (Stevens 1951). If one would wish to assess true interval-type of data instead of ordinal, nominal or ratio data, it might be argued that percent leaf damage would need to be assessed, particularly for medium and heavy damage. This is, however, subject to human bias when not done through imaging software, and therefore difficult to implement. We therefore proposed the novel 0.0 to 4.0 leaf damage index that creates data close to interval data, therefore allowing the application of some parametric statistical inference methods. Finally, most of the scales do not account for leaf numbers and none for plant maturation status, with older plants being usually more relevant economically to a farmer than younger plants. For all these reasons, some researchers argue it might be scientifically more accurate to assess the pest population itself rather than damage. This can be achieved by counting caterpillars per plant, or the total weight of caterpillars per plant (Wiseman and Davis 1979), as well as through capturing moths in traps (Prasanna et al. 2018; FAO and CABI 2019). However, the population density measures are rarely linearly correlated with damage and even less correlated with yield loss (Dent and Walton 1998). This was also confirmed by the weak relationship found between the scales studied here, and fall armyworm caterpillar populations (Fig. 1). Therefore, damage levels will likely remain the most used types of data when studying the impact of this pest.

In summary, all proposed scales have their advantages and disadvantages summarised in Table 5. Except for the 0.0 to 4.0 damage index, they all remain of nominal or ordinal data type, limiting the application of some parametric

statistical inferences. Only, the novel “0.0 to 4.0 fall armyworm leaf damage index” is of the ratio data type being more linear than the other scales. However, the associated workload when using this scale is high.

In conclusion, we suggest to use the “simple 1 to 5 whole plant damage scale” for pest monitoring and decision-making at all maize growth stages (Table 6). The original or simplified “Davis’ 0 to 9 whorl & furl damage scale” should be used for research purposes that need to estimate recent effects of treatments against caterpillars, as they are most reflected in reduction in damage in the newly grown parts of the plant, thus in the whorl and furl. The “Williams’ whole plant 0 to 9 leaf damage scale” as well as the “0.0 to 4.0 fall armyworm leaf damage index” should be used when longer periods need to be assessed on different stages of vegetative maize; and the latter scale particularly when high data resolution is required.

## Authors’ contributions

ST designed the study. PF and ST reviewed literature. ST, PF, DB, IM, JK implemented the study and collected data. ST, MS analysed the data. ST, JK, TT supervised the study. ST, PF, TT wrote the manuscript.

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**Table 6** Proposed use of leaf damage rating scales for assessing damage by fall armyworm caterpillars

Objective	Maize grow stages	Recommended scale
Pest population monitoring, decision-making	All	Yes–No damage scale Simple 1–5 whole plant damage scale
Research assessing longer periods of feeding damage, e.g. maize hybrid selection, systemic effects, cultural control effects	Vegetative	Williams’ 0–9 whole plant damage scale Toepfer & Fallet 0.0–4.0 leaf damage index
Research assessing recent feeding damage, e.g. effects of plant protection products	Vegetative	Davis’ 0–9 whorl & furl damage scale

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**Availability of data and material** All raw data are represented in the scatter plots in the manuscript.

#### Declaration

**Conflict of interest** All authors declared that they have no conflict of interest.

**Ethics approval** This article does not contain any studies with human participants or vertebrates performed by any of the authors.

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

**Consent for publication** Informed consent was obtained from all individual participants included in the study.

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