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Review

Global crop impacts, yield losses and action thresholds for fall armyworm (*Spodoptera frugiperda*): A review

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ABSTRACT

The fall armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is a highly polyphagous plant pest that can severely impact yields of several agricultural crops. Understanding the economic impact and management thresholds for FAW across a variety of crop commodities is crucial for effective management. Evaluating the peer-reviewed and grey literature, we compiled global data on: (1) yield losses reported as a result of FAW infestations, (2) the relationship between FAW pressure/density and reported yield loss, and (3) current known economic injury levels, economic thresholds and action thresholds. We identified 71 references that reported yield losses from FAW infestation, with a total of 888 separate yield loss entries. The majority of research quantifying yield losses and the relationship between pest pressure and yield has focused on maize, sorghum, and cotton, with some evidence for sweet corn, bermudagrass, and rice. Yield loss varied between management strategies, with genetically modified and/or insecticide treated crops typically retaining higher yields. Most studies investigating the relationship between FAW density and yield loss across different crops have focused on early and mid FAW larval instars and on vegetative through to reproductive plant growth stages, with minimal research on both late larval instars and on plant seedlings. Economic thresholds were not reported in the literature. The reporting of economic injury levels and action thresholds varied significantly both between and within crops, highlighting the need for a standardised approach when measuring FAW pressures or densities that elicit management responses.

1. Introduction

The fall armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is a highly polyphagous pest that reportedly attacks over 350 commercial and non-commercial hosts across 76 plant families (Montezano et al., 2018). It causes damage across a range of crop hosts including maize, *Zea mays* L. (Poales: Poaceae), sorghum, *Sorghum bicolor* (L.) Moench (Poales: Poaceae), soybean, *Glycine max* (L.) Merr (Fabales: Fabaceae), cotton, *Gossypium hirsutum* L. (Malvales: Malvaceae), barley, *Hordeum vulgare* L. (Poales: Poaceae), and wheat, *Triticum aestivum* L. (Poales: Poaceae) (Pitre and Hogg, 1983; Marenco et al., 1992; Bueno et al., 2011; Hardke et al., 2015; Yang et al., 2019a, 2019b), with graminaceous plants preferred (Montezano et al., 2018; Malo and Hore, 2020). In 2016, FAW was detected in West Africa, the first report outside of its native range of the Americas (Goergen et al., 2016). FAW rapidly spread to neighbouring countries (Cock et al., 2017) and other parts of the continent, before appearing in 2018 in the Middle East (EPPO, 2020) and India (Deshmukh and Kalleshwaraswamy, 2018; Ganiger et al., 2018; Kalleshwaraswamy et al., 2019). It has since spread throughout Asia, and in early 2020 reached mainland Australia (EPPO, 2020). Due to the rapid global invasion of FAW, there is a pressing need to understand the economic impact and management options for this species.

FAW is recognised as an important pest in its native range, with

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examples of high reported yield losses that have resulted in significant economic impacts. In the USA, Mitchell (1979) estimated the annual value of yield lost to FAW at around US$300 million, rising to US$500 million or more in major outbreak years. However, the cost of FAW management in the Americas is not easy to assess directly, as genetically modified (GM) *Bacillus thuringiensis* Berliner 1915 (*Bt*) crops and insecticides are widely used, which reduce the impact potential of FAW. In Brazil, an estimated US$600 million was spent in 2009 controlling FAW, equivalent to approximately US$40/ha (Ferreira Filho et al., 2010). In FAW's introduced range, based on farmer surveys, maize yield losses in Ghana and Zambia were estimated at US$284 and 198 million, respectively, with an extrapolated loss across 12 African countries of between US$2.5–6.3 billion in 2017 (Day et al., 2017). FAW is estimated to cause up to US$13 billion per annum in maize, rice, sorghum, and sugarcane losses across sub-Saharan Africa (Abrahams et al., 2018). Europe has regularly intercepted FAW on fresh produce from Latin America, particularly on capsicum and *Solanum* species (Abrahams et al., 2017), and since 2017 similar interceptions have been made on produce from Africa including roses (Rwomushana et al., 2018). In June 2018, Europe instigated emergency measures covering capsicum, momordica, *Solanum* species, and maize, requiring strict controls in exporting countries (Jeger et al., 2018). The economic impact of these phytosanitary measures has not yet been quantified.

The incidence and severity of any pest will determine the yield loss experienced in a given region. Incidence is the frequency of environmental conditions that enable the pest to reach economically damaging levels within the region, while severity is the level of damage caused during those periods where the pest can reach or exceed economically damaging levels (Murray et al., 2013). Typically, only a proportion of the crops grown within a particular region will be affected during a pest outbreak. In the case of FAW, direct yield losses can occur through larvae feeding on the developing or mature part of the plant that is harvested (e.g. invading the ears of maize and feeding on the cob, or feeding directly on the grain), thereby directly reducing yields (Harrison, 1984). Indirect yield losses can occur through defoliation, which can in turn reduce grain production due to a decrease in photosynthetic area (Cruz and Turpin, 1983; Pitre and Hogg, 1983; Buntin, 1986; Melo and Silva, 1987; Capinera, 2008; Vilarinho et al., 2011), and/or the loss of seedlings. Quality losses caused by FAW can also arise when larval feeding introduces saprotrophic and pathogenic fungi, which can lead to mycotoxin contamination of the grain (Farias et al., 2014). In the subtropical regions of the USA, feeding by FAW can result in the infection of maize kernels by *Aspergillus flavus* Link (1809), which can lead to significant preharvest losses (Pruter et al., 2020).

Throughout FAW's native and invasive range, economic impacts within agricultural crops can be classified into four categories: (1) direct and indirect yield loss, (2) cost of management, (3) quality loss, and (4) impacts on trade arising from phytosanitary measures required by importing countries (Murray et al., 2013; Day et al., 2017). Knowledge of the potential economic impact of FAW is important to both national and local pest management decisions. At the national scale, governments utilise such impacts in biosecurity preparedness planning and resource allocation. At the local scale, increased confidence or knowledge of the potential impact can provide farmers and industry stakeholders with the information to make informed in-field decisions about management interventions, such as action thresholds. However, like many agricultural arthropod pests, the economic impact of FAW is complicated by interactions between the host crop species, plant growth stage, pest life stage, and the environmental context (Buntin, 1986). Of the four areas of economic impact described, FAW yield loss (both direct and indirect) is likely to be the most important consideration in many cases, and it is also the area where most information is publicly available.

Here, we review the global literature on yield loss caused by FAW in both its native and invasive ranges, covering all crops for which data are reported. Specifically, we conducted two comprehensive reviews of the peer-reviewed published and grey literature to establish all publicly available data on: (1) available crop loss reports, (2) the relationships between infestation density/level and yield loss, and (3) economic injury levels and management thresholds currently in use for FAW. A thorough understanding of existing reported yield losses for impacted crops as well as varying densities of FAW that warrant management intervention will allow for improved preparedness and mitigation of potential yield losses, particularly in countries where these impacts are yet to be quantified.

2. Methods

2.1. Review of yield loss data

To identify the impact of FAW on the yield loss of crops, we used the following search terms in Web of Science: (1) "spodoptera frugiperda AND (yield OR impact OR damage OR econom* OR losses)", and (2) "spodoptera frugiperda AND (pesticide OR insecticide OR management) AND yield", which yielded 1102 and 87 peer-reviewed journal articles, respectively. The literature searches were conducted between April and May 2020, respectively. We conducted a second literature search to identify experiments that examined insecticide efficacies against FAW, which typically included a positive control (i.e. an insecticide previously identified to have high efficacy, or the yield derived from a plot that was not infested with FAW), which could then be used to calculate yield loss. Titles and abstracts of all journal articles were screened manually to identify relevant sources, which were then scrutinised in detail. Yield loss data were extracted or, when not explicitly provided, calculated based on the available information. Calculations of the proportion of yield loss were determined by dividing the observed yield by the positive control (or uninfested plot) yield. If a yield loss range was expressed (e.g. 20–50%), we calculated the mean yield loss (e.g. 35%).

Within each article, we scrutinised the text and reference list to identify other potential references which may not have been captured through our Web of Science search. To identify industry reports or resources, we conducted Google searches for "fall armyworm impact yield loss" for the USA, South America, Africa, and Asia.

After each source was identified, various parameters were recorded (Table 1). A qualitative measure was integrated into our analysis for the 'confidence level' of each yield loss observation to determine if the observation method influenced yield loss estimates. The confidence level of various reported yield losses was only compared for maize, as all other crops had two or less instances where differing confidence levels occurred, and therefore not enough data was available to draw meaningful comparisons. Additionally, we incorporated a 'management strategy' categorical variable to capture the influence of various management strategies on yield loss (Table 1). This dataset was summarised visually to highlight variation with crop, data confidence, report date, and location. Countries with fewer than 10 reports were pooled together as "Other". Negative crop loss values (e.g. when impacted plots yielded higher than the control) were truncated at zero when plotted. Where only approximate locations were provided, spatial coordinates were inferred from the location name.

2.2. Review of pest pressure and threshold data

Using Web of Science, we conducted a literature search in May 2020 using the search term "spodoptera frugiperda AND econom* AND (yield OR threshold* OR injur*)", which yielded a total of 46 peer-review journal articles. We conducted additional searches in Google Scholar in May 2020 using the terms "spodoptera frugiperda threshold", "spodoptera frugiperda action", and "spodoptera frugiperda treatment" to ensure all relevant scientific journal articles were captured and to also accumulate relevant information in the grey literature from industry publications or reports. In studies where the relationship between pest pressure and yield loss was investigated, these were scrutinised and

Table 1
Data fields used to guide compilation of relevant experimentally derived or reported yield loss data as a result of fall armyworm infestation reported in the published and grey literature.

Data field	Description
Scientific plant name	*Genus species*
Common plant name	Names commonly used to identify the plant
Variety	Plant variety
Context	Context of the plant: commercial/non-commercial
Proportion of yield loss reported	Yield loss (reported as a proportion)
Site	Site where yield loss was reported (if applicable; e.g. Name of experimental research station)
City	City where yield loss was reported (if applicable)
Area/province/municipality/district	Area/province/municipality/district where yield loss was reported (if applicable)
Part of the State where yield loss was reported (if applicable)	Central, North, South, East, West, etc.
State	State where yield loss was reported (if applicable)
Climactic/topographic zone	The climactic/topographic zone where the yield loss was reported (if applicable)
Country	Country where yield loss was reported
Latitude	Latitude of the site
Longitude	Longitude of the site
First FAW detection	Year FAW was first detected at this location
Year	Year the experiment/yield loss was reported/determined
Assumptions	Any assumptions made to determine/calculate yield loss
Confidence level	Confidence level of the reported/calculated yield loss (**high** = yield loss has been experimentally derived, **medium** = a yield loss has been inferred from the damage levels assessed in the host OR surveys/reports of farmers perception of yield loss, **low** = personal communication of a yield loss reported in a journal article where no data is available or published to verify the accuracy of yield loss)
Management strategy	Management strategy/strategies used: insecticides, biological control, cultural, GM (*Bt*), variety (variety of crop sown), unmanaged, or unknown. Studies that were classified as 'unknown' were either due to the reported yield losses derived from review papers where the original articles could not be accessed, or they were mean yield losses reported from farmer surveys and did not capture the variety and extent of management strategies in place. For some studies, multiple management strategies were utilised (e.g. insecticide treatment in a GM crop).
Source/reference	Source of information

recorded using the parameters outlined in Table 1. Further, we also recorded or derived the following information where available: (1) plant growth stage, (2) FAW life stage, (3) number of FAW per plant, (4) number of plants per hectare, (5), number of FAW per hectare, (6) FAW density (number per hectare), (7) pest pressure description/type (density, infestation percentage, or number of FAW per plant), (8) treatment yield (i.e. yield observed when crops were exposed at the specified FAW density), (9) control yield (i.e. yield observed when FAW density/pressure was zero), (10) percentage of yield loss (calculated by dividing treatment yield by control yield and multiplying the proportion by 100 to determine the percentage of yield loss), and (11) if the yield loss was reported as statistically significant. Where FAW pressure was recorded as infestation percentage or the number of FAW per plant, if there was sufficient information to calculate the number of plants per hectare, we standardised pest pressure as density. This was achieved by calculating the number of plants per hectare, and then extrapolating an estimate of the number of FAW per hectare. Plant growth stage was categorised as early (emerging/seedling stages), mid (vegetative stages), or late (reproductive stages). FAW life stage was categorised as early (first and second instars), mid (third and fourth instars), or late (fifth and sixth instars). Where FAW life stage was provided as a range that encompassed two categories, they were classified across the range, e.g. third to sixth instars or fourth to fifth instars were classified as mid-late instars. If plant growth stages and FAW life stages were not provided, they were classified as 'unspecified'. To aid visualisation of trends in the data which shows yield reduction caused by FAW, a linear regression line was plotted for each unique pest pressure metric, crop group, and plant growth stage.

2.3. Economic injury levels, economic thresholds and action threshold data

As part of the review of FAW pest pressure and threshold data, we collected data on economic injury levels, economic thresholds and action thresholds for FAW. This was undertaken by recording the following information for each reference and is summarised in Table 2: (1) crop, (2) management threshold type (economic injury level 'EIL', economic threshold 'ET' or action threshold 'AT'), (3) the location of the reported management threshold (i.e. country), (4) plant variety, (5) plant growth stage, (6) FAW life stage, (7) threshold reported, and (8) any additional pertinent information.

In our study, the EIL was defined as the number of FAW individuals (or amount of injury) that will cause yield losses equal in value to the pest management costs, and is expressed by the formula:

$$\mathrm{EIL} = \frac{\mathrm{C}}{(\mathrm{V} \times \mathrm{I} \times \mathrm{D} \times \mathrm{K})}$$

Where C = cost of management per unit of production (e.g. \$/ha), V = the value of the crop (e.g. \$/kg), I = injury (damage) per insect per production unit (e.g. [kg reduction/ha]/proportion defoliated), and K = the proportional reduction of the population due to control (Huesing et al., 2018). Estimates of parameters C and V are highly dependent on the context, while K depends on the effectiveness of control. Therefore, the EIL varies within local contexts.

The ET is the pest density (or level of injury) at which control measures should be initiated to prevent populations reaching the EIL (Huesing et al., 2018). However, precise quantification is rarely feasible, so it is common for an AT to be used, which is the pest density (or level of injury) at which a control intervention should be made. Not all thresholds in use are derived formally in this way, with many derived instead from expert opinion and/or farmer experience (i.e. nominal thresholds; Miles, 2014). Thus, we collated published information on EILs, ETs, and ATs (Table 2), to provide examples which might be used as a starting point in countries where FAW has recently invaded and farmers require guidance.

3. Results

3.1. Yield loss

We identified 71 peer-reviewed references that reported yield losses from FAW infestation, with a total of 888 separate yield loss entries. Despite the literature search encompassing all commercial hosts, we did not find any reported yield losses in horticulture crops (with the exception of sweet corn), ornamental crops, and turfgrasses (with the exception of bermudagrass), despite dozens of these species reported as FAW host plants (Montezano et al., 2018). Overall, we found a wide global distribution of reported yield losses due to FAW, with reports concentrated in the USA, South America and Africa (Fig. 1). The vast majority of studies have examined maize, followed by cotton, sorghum, and sweet corn.

Table 2
Economic injury levels, economic thresholds and action thresholds identified in the literature (peer-review and grey) for fall armyworm (FAW) across a variety of crop commodities. A blank entry signifies information/data that was not supplied in the reference. No economic thresholds (ET) were identified.

Crop	EIL, ET or AT	Location	Plant variety	Plant lifecycle stage	FAW lifecycle stage	Threshold reported	Additional information	References
Maize	EIL	Maryland, USA	Single cultivar (DeKalb T-1100) planted from 1988 to 1990. Mixed-cultivar (Dekalb T-1100, Augusta A613, Pioneer 3343, Pioneer 3140, Pioneer 3475) planted in 1990	Mid-whorl and late-whorl	2nd instar	2 larvae/plant in 1988, 1989 and 1990	EIL varied for maize priced at higher value, and higher EILS were established when the cost of control was greater	Pereira and Hellman (1993)
	EIL	Maryland, USA	Single cultivar (DeKalb T-1100) planted from 1988 to 1990. Mixed-cultivar (Dekalb T-1100, Augusta A613, Pioneer 3343, Pioneer 3140, Pioneer 3475) planted in 1990	Late-whorl	2nd instar	2 larvae/plant in 1988 and 1990	EIL varied for maize priced at higher value, and higher EILS were established when the cost of control was greater	Pereira and Hellman (1993)
	EIL	Espinal, Colombia	30F35R (non-*Bt*)			2.6 larvae per 10 plants	EIL for first growing cycle	Jaramillo-Barrios et al. (2020)
	EIL	Espinal, Colombia	30F35R (non-*Bt*)			1.9 larvae per 10 plants	EIL for second growing cycle	Jaramillo-Barrios et al. (2020)
	EIL	Espinal, Colombia	30FS35HR (*Bt*)			2.8 larvae per 10 plants	EIL for first growing cycle	Jaramillo-Barrios et al. (2020)
	EIL	Nicaragua				Range of EIL from 23 to 63%	When plants infested with both FAW and *Diatraea lineolata* (Walker) (Lepidoptera: Crambidae), across multiple potential yields (range from 750 to 2000 kg/ha) using an average insecticide efficacy of 75%	Hruska and Gould (1997)
	EIL	Quevedo, Ecuador		2 weeks after germination		15% infestation		Evans and Stansly (1990)
	EIL	Quevedo, Ecuador		3 weeks after germination		21% infestation		Evans and Stansly (1990)
	EIL	Quevedo, Ecuador		4 weeks after germination		23% infestation		Evans and Stansly (1990)
	EIL	Quevedo, Ecuador		5 weeks after germination		26% infestation		Evans and Stansly (1990)
	EIL	Quevedo, Ecuador		6 weeks after germination		50% infestation		Evans and Stansly (1990)
	EIL	Nicaragua				2% infestation	EIL was very low due to high subsidies provided for insecticides in Nicaragua at the time of the experiment	Hruska and Gladstone (1988)
	AT	Brazil		Stages equal to or less than 30 days after planting		20% of plants with damaged leaves		Gallo et al. (2002)
	AT	Brazil		Stages between 40 and 60 days after planting		10% of plants with damaged leaves		Gallo et al. (2002)
	AT	Arkansas, USA				3 to 6 larvae per whorl of maize		Studebaker (2021)
	AT	Africa		Early whorl		Damage/injuries reach 20%	For smallholder farmers	McGrath et al. (2018)
	AT	Africa		Late whorl		Damage/injuries reach 40%	For smallholder farmers	McGrath et al. (2018)
	AT	Africa		Tassel and silk stage		No treatment unless insecticide has low toxicity	For smallholder farmers	McGrath et al. (2018)

(continued on next page)

Table 2 (*continued*)

Crop	EIL, ET or AT	Location	Plant variety	Plant lifecycle stage	FAW lifecycle stage	Threshold reported	Additional information	References
						and/or is supportive of conservation biological control		
	AT	Africa		Early whorl		Damage/injuries reach 20%	For village level/larger scale farmers	McGrath et al. (2018)
	AT	Africa		Late whorl		Damage/injuries reach 40%	For village level/larger scale farmers	McGrath et al. (2018)
	AT	Africa		Tassel and silk stage		Damage/injuries reach 20%	For village level/larger scale farmers	McGrath et al. (2018)
Sorghum	EIL	Mississippi, USA		5 leaves (growth stage 2)	4th instar larvae	1.1 larvae per plant	Monte Carlo simulations were performed to predict EIL	Zeledon (2004)
	EIL	Mississippi, USA		8 leaves (early growth stage 3)	4th instar larvae	2.5 larvae per plant	Monte Carlo simulations were performed to predict EIL	Zeledon (2004)
	EIL	Mississippi, USA		10 leaves (late growth stage 3)	4th instar larvae	3.9 larvae per plant	Monte Carlo simulations were performed to predict EIL	Zeledon (2004)
	EIL	Mississippi, USA		Plants less than 38 cm		1 larva per plant	Reported economic threshold for FAW in sorghum in Mississippi	Zeledon (2004)
	AT	Mississippi, USA				1 (or 2) larvae per leaf whorl, or two per head of sorghum		Pitre (1984)
	AT	Oklahoma, USA		Late vegetative stages		2 larvae per plant	An average of 2 larvae/ plant during late stage of plant development can do enough economic damage to justify chemical control	Starks and Burton (1979)
	AT	North & South America		Headed		2 larvae per head		Young and Teetes (1977) and Teetes and Wiseman (1979)
	AT	Georgia, USA		Sorghum seedlings		10% of plants with egg masses		Martin et al. (1980)
	AT	Georgia, USA		Whorl/shoot stage		1 larva per plant		Martin et al. (1980)
	AT	Georgia, USA		Head growth stage		2 larvae per plant		Martin et al. (1980)
	AT	Arkansas, USA				1 larva that is greater than 0.5 inches per head		Studebaker (2021)
Wheat	AT	Arkansas, USA				5-6 larvae per square foot		Studebaker et al. (2016)
	AT	Kansas, USA				Windowpane injuries are observed in 25–30% of plants warrants treatment to prevent stand loss		Zukoff et al. (2019)
Peanuts	AT	Arkansas, USA				FAW exceeds 4 per foot within a row and foliage loss exceeds 15%		Studebaker (2021)
Soybeans	AT	Arkansas, USA		Pre-bloom		50% defoliation		Studebaker (2021)
	AT	Arkansas, USA		Post-bloom		25% defoliation		Studebaker (2021)
Rice	AT	Arkansas, USA		Seedling to 2–3 tiller		No action threshold	No action threshold during vegetative stages of rice as there is no resulting yield loss, unless FAW is feeding on the growing point.	Studebaker (2021)
	AT	Arkansas, USA		5-6 tiller		Defoliation exceeds 40%		Studebaker (2021)

(*continued on next page*)

Table 2 (*continued*)

Crop	EIL, ET or AT	Location	Plant variety	Plant lifecycle stage	FAW lifecycle stage	Threshold reported	Additional information	References
							This threshold is relevant for May and June plantings	
	AT	Arkansas, USA		Green ring		Defoliation exceeds 20%	This threshold is relevant for May and June plantings	Studebaker (2021)
Cotton	AT	Arkansas, USA				10-20 FAW per 100 plants		Studebaker (2021)
Alfalfa	AT	Arkansas, USA		Seedling alfalfa		2 larvae per square foot		Studebaker (2021)
Pasture and hay meadows	AT	Arkansas, USA				2 or more FAW per square foot, or 1 FAW per sweep with a 15-inch sweep net	Pasture and hay meadows includes bermudagrass, fescue, Sorghum spp., cool season grasses, ryegrass, winter wheat, mixed grass	Studebaker (2021)

3.1.1. *Maize*

Impacts of FAW feeding in maize have been reported across the broadest geographic range (both native and invasive ranges) compared with other commercial hosts (Fig. 1; Fig. 2). Through time, reported and/or experimentally derived crop losses were frequently quantified from 1980 to 2000, with no obvious trends in the number of studies. However, from 2000 to 2015, there was a reduction in the number of studies reporting crop losses (Fig. 3). We found no studies quantifying yield losses from FAW prior to 1980. Since 2016, there has been a considerable increase in the number of studies reporting yield loss (Fig. 3), correlating with FAW's recent invasion outside its native range (Fig. 1). Relatively little yield loss data have been reported in Asia to date, which contrasts with Africa where we identified numerous reports of yield loss (Fig. 1). When comparing maize yield losses assigned as high confidence (experimentally derived yield losses) and medium confidence (interviews/surveys of yield losses experienced by farmers), we found large differences in the mean reported crop losses of 17.31 ± 0.90% (mean ± SE) and 35.57 ± 2.45%, respectively (Fig. 4). This suggests that when crop losses have been reported through farmer surveys, yield losses as a result of FAW may be overestimated, with more than double the yield losses compared with those established through experimental trials. While we identified and assigned three reported yield losses as low confidence level, as no information was provided on how the yield loss was established, we have not included the mean

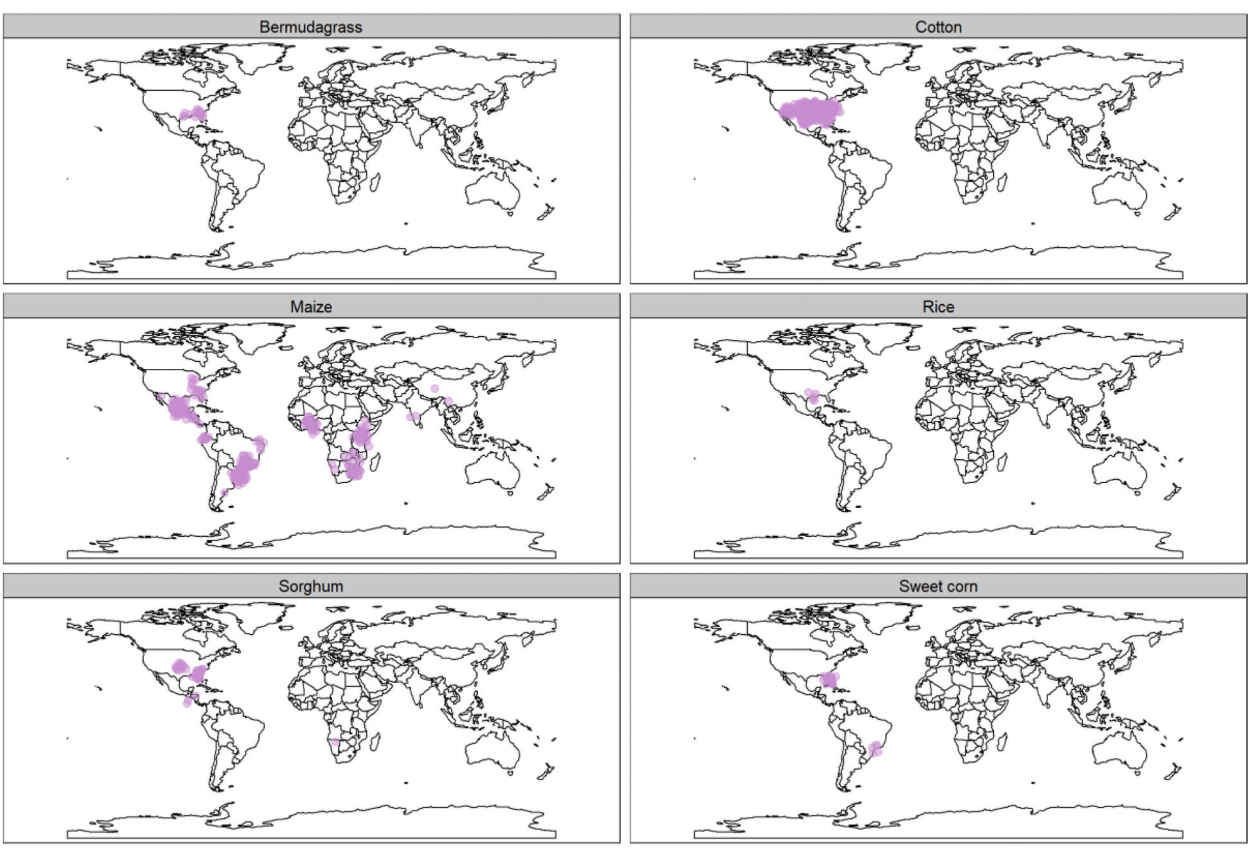


Fig. 1. Global fall armyworm crop losses reported by locality for bermudagrass, cotton, maize, rice, sorghum, and/or sweet corn globally.

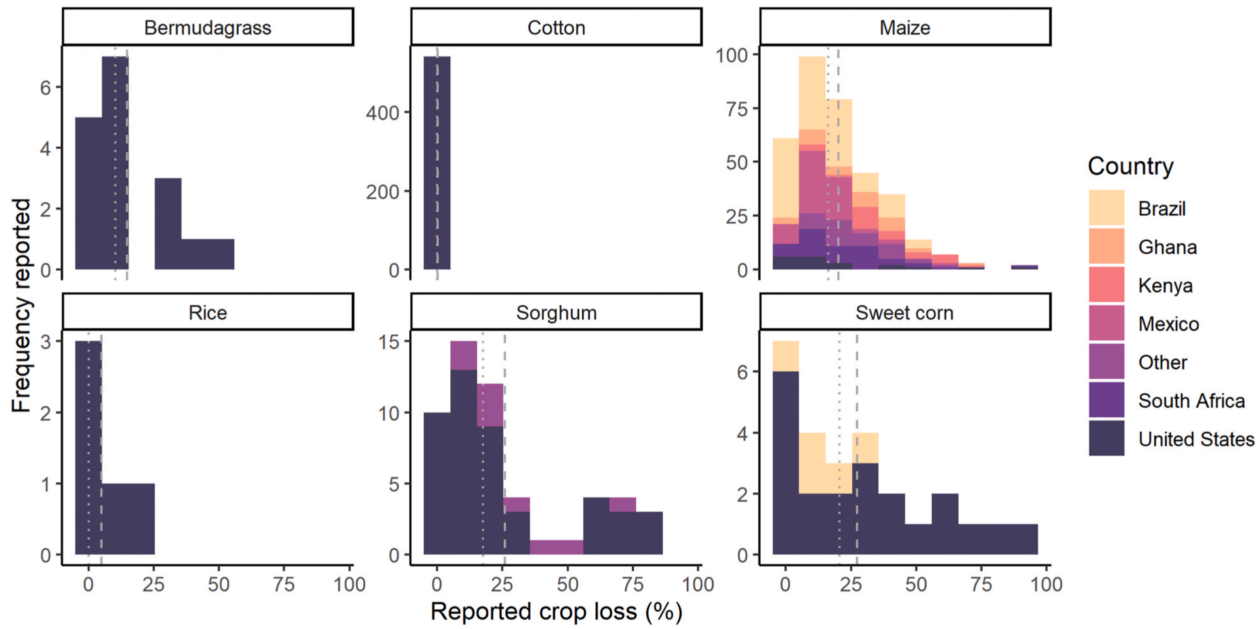


Fig. 2. The frequency (count) of cases reporting crop losses as a result of fall armyworm infestation for bermudagrass, cotton, maize, rice, sorghum and sweet corn for countries where reported. Countries were classified as 'other' if the number of reports across commodities was less than 10, and consist of: (1) maize: India, Argentina, Zimbabwe, Ethiopia, China, Ecuador, Nicaragua, Panama, and Zambia, and (2) sorghum: El Salvador, Namibia and unspecified South American countries. The dashed and dotted vertical lines represent the overall mean and median reported loss for, respectively, each crop.

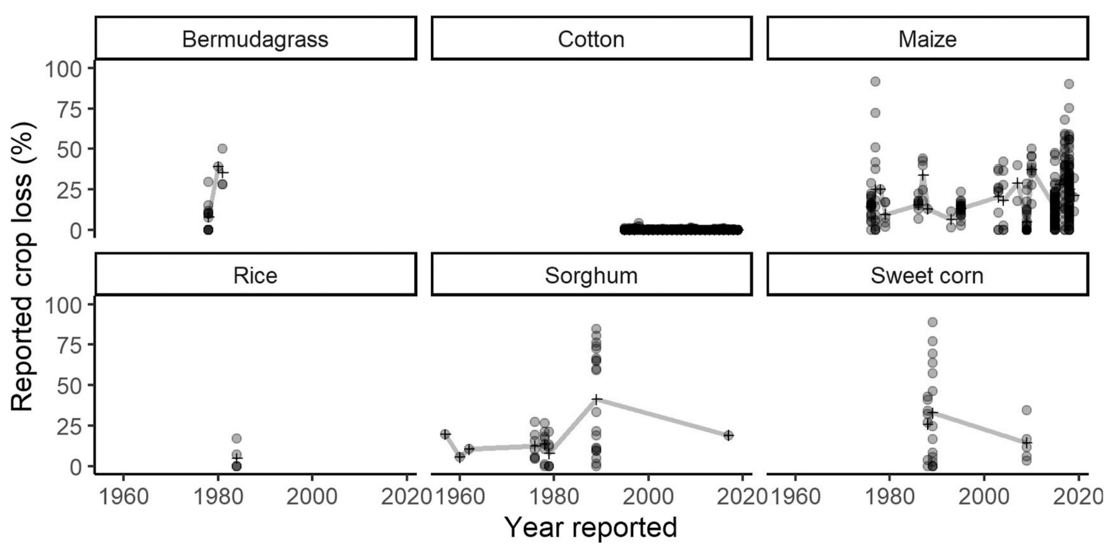


Fig. 3. Crop losses (%) reported as a result of fall armyworm infestation for bermudagrass, cotton, maize, rice, sorghum and sweet corn, each year from 1957 to 2020. Shaded circles represent individual reports of yield loss, the plus (+) symbols represent the mean crop loss (%) for the year reported, and the solid grey line represents an interpolated spline of yield loss reported each year.

reported crop loss for this confidence level.

FAW yield losses were highest in maize where management practices were not specified (i.e. management was unknown; 34.11 ± 2.35%), followed by unmanaged non-GM crops (25.17 ± 2.06%), and non-GM crops managed with insecticides (21.26 ± 2.06%; Fig. 5). The majority of studies where management practices were unspecified were derived from farmer surveys. Mean yield losses were low for GM maize managed with and without insecticides (11.07 ± 1.05% and 13.45 ± 3.62%, respectively; Fig. 5). Despite several studies examining the yield losses experienced in GM maize conducted between 2009 and 2017 (Burtet et al., 2017; Michelotto et al., 2017; Teixeria Silva et al., 2020), it is important to note that resistance to the *Bt* toxin Cry1F was first detected in 2010 in Puerto Rico (Storer et al., 2010) and in 2014 in Brazil (Omoto et al., 2014). While the *Bt* toxin Vip3A remains effective, some recent studies have reported increased frequencies of resistance alleles in Brazil (Bernardi et al., 2015; Amaral et al. 2020). Further, despite most *Bt* traits remaining effective against FAW, it is important to note that the loss of efficacy in some GM maize varieties and the resulting impact of *Bt*-resistant FAW on yield loss is therefore not reflected in Fig. 5.

Several studies have tested FAW susceptibility of different maize varieties, with a mean reported crop loss of 9.80 ± 1.13% (Fig. 5). Our inclusion of studies designed to identify efficacious insecticides to control FAW has likely resulted in an overinflation of yield losses reported, given that we included data from these trials where certain insecticides were not effective, and therefore did not prevent yield loss (i.e.

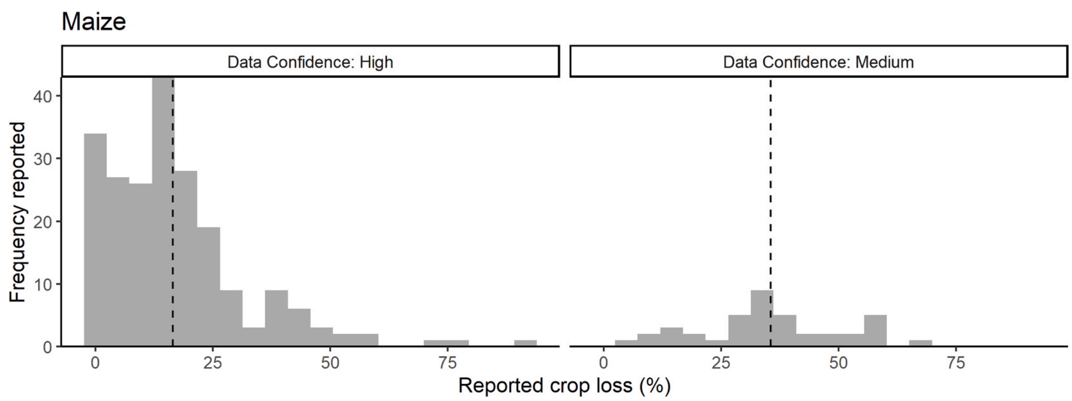


Fig. 4. The frequency (number of entries) of cases reporting of crop losses in maize due to fall armyworm infestations derived through high confidence methodologies (i.e. experimentally derived yield losses), and medium confidence methodologies (i.e. reported estimates of yield losses by farmers conducted through surveys).

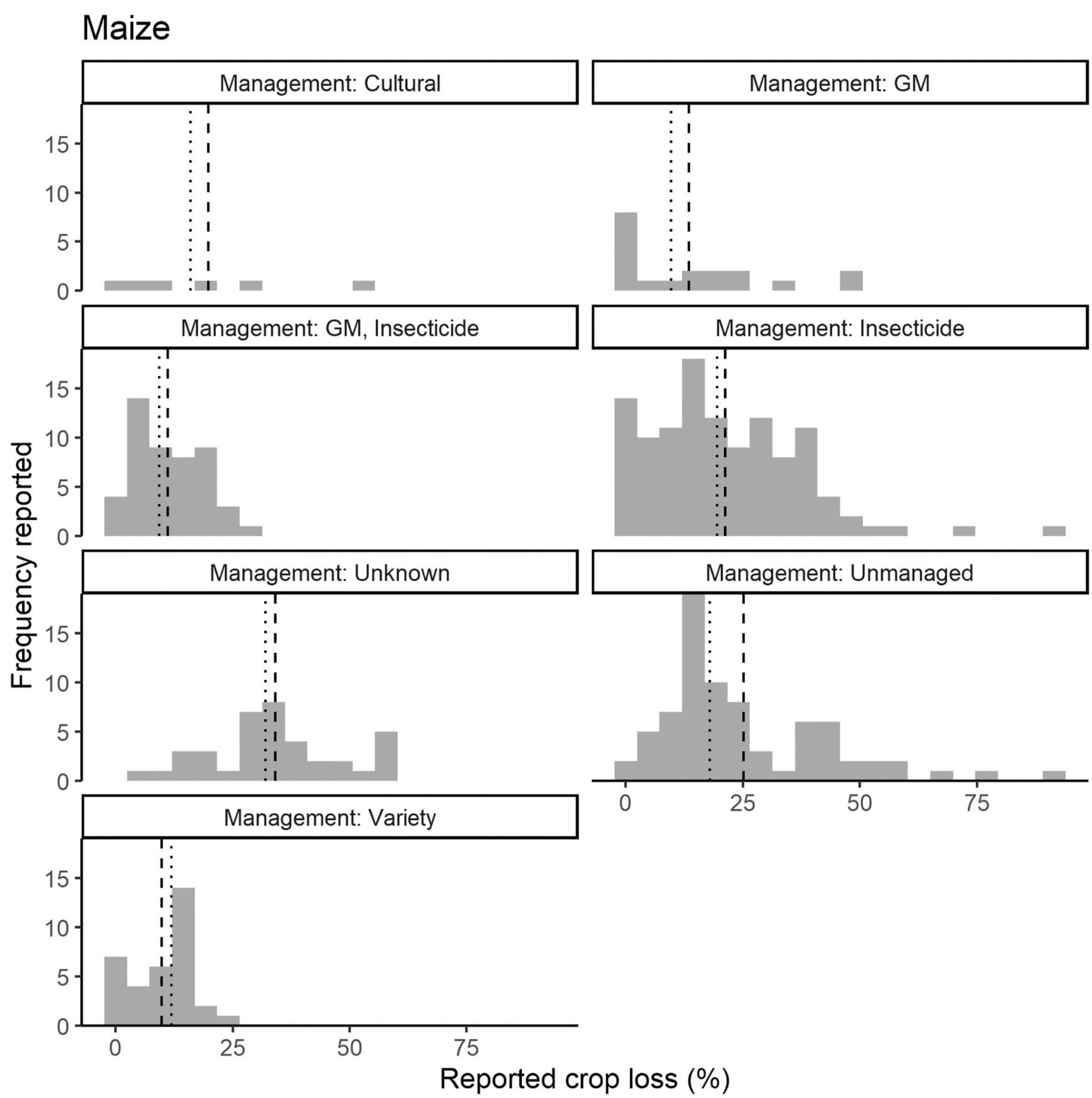


Fig. 5. The frequencies (count) of reported crop losses for maize due to fall armyworm infestations globally under different management strategies (GM, insecticide, unmanaged, unknown, and non-GM variety). The 'GM, Insecticide' group indicates that both management strategies were utilised (i.e. GM crops were sprayed with insecticide(s)). The dashed and dotted vertical lines represent the mean and median reported crop loss, respectively.

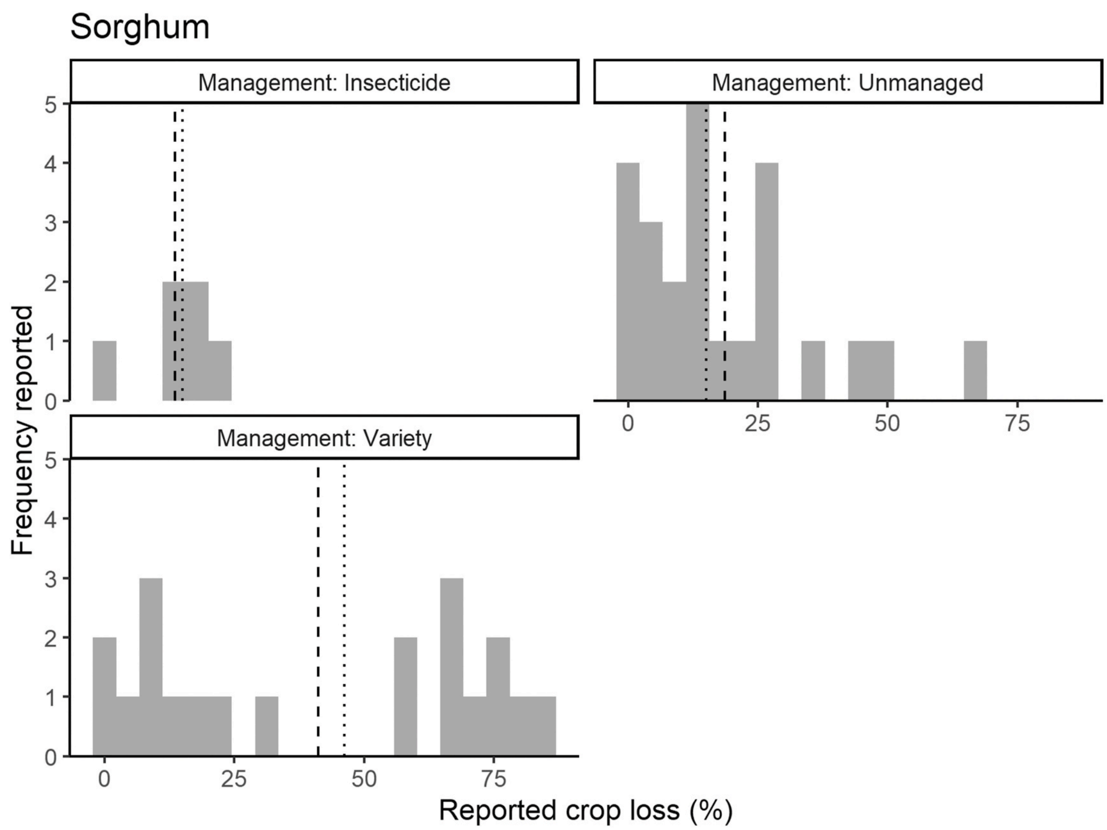


Fig. 6. The frequency (count) of reported crop loss for sorghum due to fall armyworm infestations globally under a range of management strategies (insecticide, unmanaged, and variety). The dashed and dotted vertical lines represent the mean and median reported crop loss, respectively, for each crop.

Management: Insecticides; 21.26 ± 1.50%; Fig. 5). Very few studies have examined the effects of biological (n = 1; Teixeira Silva et al., 2020) and cultural (n = 2; Cruz et al., 1999; Kumar and Mihm, 2002) control practices on FAW in maize where yield losses were recorded, and therefore not enough data were available to draw meaningful comparisons.

3.1.2. Sorghum

In sorghum, the mean reported crop loss is 25.88 ± 3.42% (Fig. 2), with the majority of the research quantifying FAW impacts conducted in the USA, and several reports also identified from South America and Namibia (Fig. 1). Reported crop losses have varied through time, with a peak in observations correlating with the timing of research programs (Fig. 3). Yield loss data that have been reported are highly variable (Fig. 3), reflecting inconsistencies between studies and differing impacts, probably reflecting the different FAW densities and plant growth stages between studies. For example, sorghum plants infested 10–20 days after planting with 16 neonate larvae per plant showed no reduction in yield (Buntin, 1986). However, in the same study, when plants were infested with 2 and 36 neonate larvae 30–36 days after planting (whorl stage), FAW infestations resulted in 21 and 44% loss, respectively. Further, in two separate studies conducted in the USA, Martin et al. (1980) observed between 14 and 21% yield loss across a range of infestation pressures, while Henderson et al. (1966) observed yield losses of 19.6, 5.4, and 10.5% in whorl stage sorghum in 1957, 1960, and 1962, respectively. In contrast, an experiment conducted in El Salvador found yield losses of 50, 25 and 15% when sorghum was infested with FAW at the same infestation pressure at 13–22, 30–41, and 45–55 day old plantings, respectively (Hueso de Mira and Lainez, 1980).

When comparing FAW-induced yield losses from studies with different management practices, losses were highest when examining sorghum varieties (41.19 ± 7.00%; Fig. 6), although results were highly variable (Fig. 6). Yield losses ranged from 64.8 to 94.7% when 25 neonates were placed in sorghum whorls 26 days after planting, and between 59.8 and 76.4% when the same infestation pressure occurred in plants 33 days after planting, highlighting the greater susceptibility of earlier plant growth stages (Diawara et al., 1991). Mean sorghum yield losses were smallest across insecticide managed crops (13.50 ± 3.02%), followed by unmanaged crops (18.64 ± 3.44%) (Fig. 6). The influence of GM, biological and cultural control strategies on reducing yield losses in sorghum by FAW have not been studied.

3.1.3. Sweet corn

Like maize, sweet corn can experience significant yield losses due to FAW feeding (up to 76.9%; Marenco et al., 1992), with a mean reported crop loss of 24.35 ± 6.28% (Fig. 3). In the sole study we found quantifying yield loss in sweet corn, feeding damage from FAW infestations during the early (V1-6) and mid-whorl stages (V7–V9), resulted in significant reductions in plant height, leaf area, and stalk diameter (Marenco et al., 1992). Furthermore, the authors showed that protecting plants from FAW damage during the late whorl stage (V9-R1) by using insecticides (methomyl) resulted in higher yields and also reduced percentages of ears damaged, and was more important than protecting plants at the early (V1–V6) and mid whorl (V7–V9) stages.

3.1.4. Cotton

All data quantifying yield losses in cotton due to FAW infestation were derived from annual reports presented at the annual Beltwide Cotton Conference, USA. FAW induced yield losses, along with area infested, the average number of insecticide applications, and number of bales lost, are reported on a region or state basis. Yield loss within infested plots are collected by state coordinators who conduct surveys of extension specialists, county agents, private consultants, and research entomologists. Analysing this data, we found that yield losses were variable across different states and years (Fig. 3; Supp. Fig. 1). Overall, yield losses observed in cotton grown in the USA were very low relative to other crops, with losses experienced typically <1% (Figs. 2 and 3). However, as these reported yield losses relied on self-reporting, the confidence level of the data is lower (i.e. medium confidence level) than if losses had been derived from experimental trials (i.e. high confidence level).

3.1.5. Rice

Very little research quantifying yield losses caused by FAW in rice have been reported (Figs. 2 and 3), with a mean yield loss of 4.82 ± 3.36% reported across all studies (Fig. 3). The few studies on rice are all in the USA (Fig. 1). A strong relationship between yield losses and FAW density were shown in Louisiana, USA, with densities of 80.7 larvae/m^2 and 215.1 larvae/m^2 resulting in 7.0% and 17.1% yield loss, respectively (Pantoja et al., 1986). While FAW has been documented to feed on both leaves and rice panicles (McCullars, 2019), most studies have focused on the effect of indirect yield losses through artificial mechanical defoliation (Gross et al., 1982; McCullars, 2019), as opposed to experimentally derived yield losses as a result of FAW feeding. There is currently no data available on rice yield losses outside of FAW's native range, and could be because FAW may not be causing significant yield loss impacts in its invasive range.

3.1.6. Bermudagrass

Research surrounding yield losses associated with FAW in bermudagrass was largely conducted during the 1980s, with reported losses ranging from 0 to 50%, and a reported mean yield loss of 12.82 ± 4.24% (Fig. 3). Similar to rice, all studies examining the impacts of FAW on bermudagrass have been conducted in the USA (Fig. 1). Yield loss impacts vary with plant growth stage (Martin et al., 1980), FAW life stage (Alvardo et al., 1983), and FAW density (Martin et al., 1980). Typically, yield losses are associated with higher FAW densities, earlier instar larvae stages (third to sixth instars resulted in mean yield losses of 828 mg per larva compared to sixth instars which resulted in 426 mg per larva), and earlier plant growth stages (Martin et al., 1980; Alvardo et al., 1983).

3.2. Relationship between pest density and yield loss

We identified data that directly examined the relationship between FAW density/presence and resulting yield loss for maize, sorghum, rice and bermudagrass across different plant growth stages. No studies were found where this was undertaken for sweet corn or cotton.

3.2.1. Maize

In maize, reported yield losses varied across FAW life stages and plant growth stages (Fig. 7). Generally, as pest density/pressure increases, yield losses also increase. Most studies have concentrated on mid plant growth stages (i.e. the vegetative stages), where a clear positive relationship is evident between yield loss and pest density (Fig. 7). At later growth stages (i.e. reproductive stages), yield losses remain relatively consistent (at approximately 16%) despite increasing pest pressure (Fig. 7). The plant growth stages and/or FAW life stage for several studies were not specified; this is particularly evident in studies that reported FAW as percentage infestation, where in some instances, both plant growth stage and FAW life stage were not specified (Fig. 7). This limits our understanding of how these factors influence yield losses in maize. We were unable to identify studies examining the relationship between FAW density and yield loss during early plant growth stages (i.e. emergence/seedlings), highlighting another significant gap.

3.2.2. Sorghum

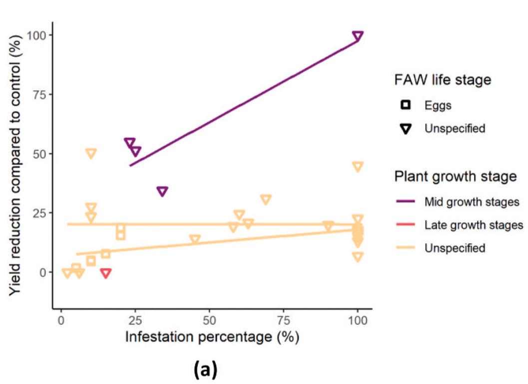
All studies on sorghum examined mid plant growth stages (i.e. vegetative stages), and similar to maize, show that increasing pest pressure results in an increase in yield loss (Fig. 8). The variation in yield loss was considerably higher across sorghum compared with those observed in maize. This was particularly noticeable when FAW densities were very high (Fig. 8), with crop loss varying from 1.4% to 84.7% (Fig. 8). Most sorghum studies failed to record the life stage of FAW, which limits our interpretation of the data. A further gap is the lack of data surrounding early (i.e. emergence/seedlings) and late (i.e. reproductive stages) plant growth stages.

3.2.3. Rice

A clear relationship between increasing pest pressure resulting in increasing yield loss is evident for rice (Fig. 9). This was observed in a trial with mid FAW larval instars during the late plant growth stages of rice, and also in another trial where defoliation was simulated mechanically. Similar positive relationships were observed for both mid and late growth stages of rice when using simulated infestation levels (Fig. 9). Rice is the only crop where early plant growth stages were investigated to establish the relationship between pest density and yield loss, with increasing defoliation resulting in higher yield losses (Fig. 9).

3.2.4. Bermudagrass

As FAW pressure increases, so does yield loss in bermudagrass across multiple lifecycle stages (Fig. 10). Most studies on bermudagrass failed to record the plant growth stage, although the trend was similar between unspecified plant growth stage and trials undertaken on mid growth stages (Fig. 10).



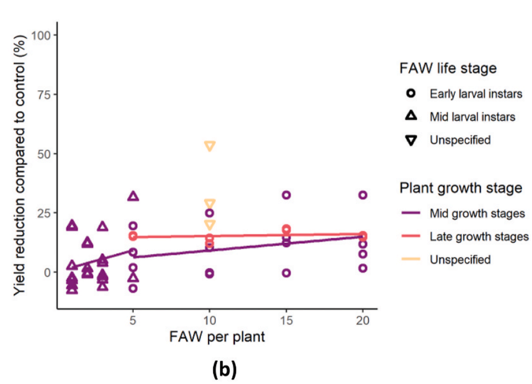


Fig. 7. Yield reduction caused by fall armyworm (FAW) in maize under variable pest pressure (i.e. density) and inoculation stage of FAW for different plant growth stages, where pest pressure has been reported as (a) infestation percentage (%), or (b) FAW per plant. The reported FAW inoculation stage of eggs and larval instars and plant growth stages are represented by different shapes and colours, respectively. Plant growth stages are categorised as early (emerging seedling), mid (leaf and stem development/vegetative stage), and late (flowering, grain development and maturation), or unspecified growth stages. FAW larval instars are classified as early instar (first & second), mid instar (third & fourth), mid-late instar (third-sixth), and late instar (fifth & sixth) stages.

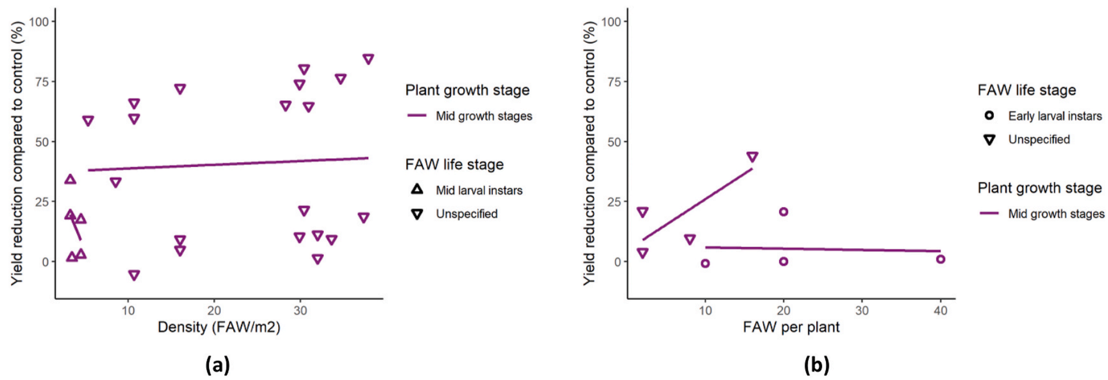


Fig. 8. Yield reduction caused by fall armyworm (FAW) in sorghum under variable inoculation stages of FAW and for mid (leaf and stem development/vegetative stage) plant growth stages, where pest pressure has been reported as (a) density (FAW/m^2), or (b) FAW per plant. The reported FAW larval instars and plant growth stages are represented by different shapes and colours, respectively. FAW larval instars are classified as early instar (first & second), mid instar (third & fourth), mid-late instar (third-sixth), and late instar (fifth & sixth) stages. Early and late plant growth stages are not visible as no data was found.

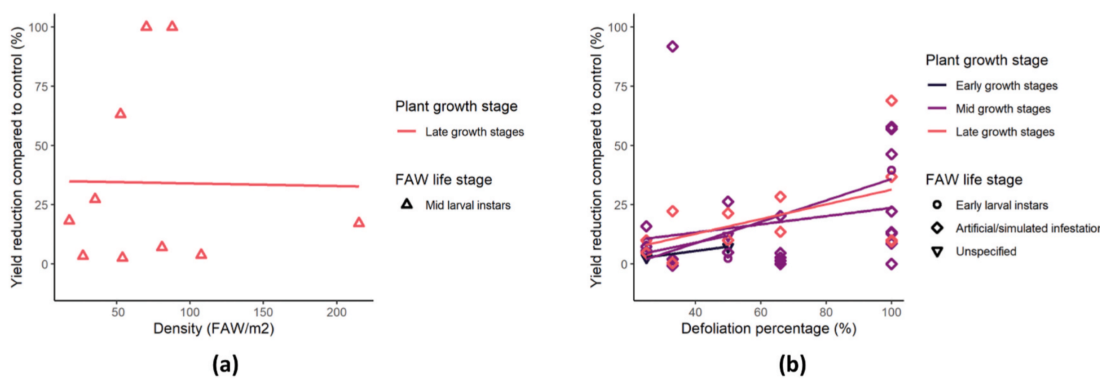


Fig. 9. Yield reduction caused by fall armyworm (FAW) in rice under variable inoculation stages of FAW and for different plant growth stages, where pest pressure has been reported as (a) density (FAW/m^2), or (b) defoliation percentage (%). The reported FAW larval instars and plant growth stages are represented by different shapes and colours, respectively. Plant growth stages are categorised as early (emerging seedling), mid (leaf and stem development/vegetative stage), and late (flowering, grain development and maturation) growth stages. FAW larval instars are classified as early instar (first & second), mid instar (third & fourth), mid-late instar (third-sixth), and late instar (fifth & sixth) stages.

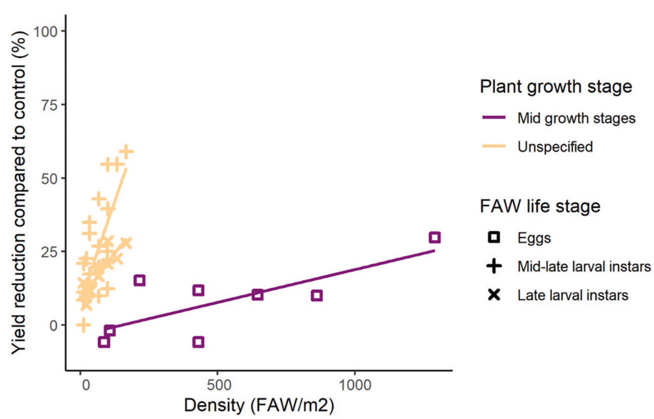


Fig. 10. Yield reduction caused by fall armyworm (FAW) in bermudagrass under variable pest pressure (i.e. density (FAW/m^2)) and inoculation stages of FAW for different plant growth stages. The reported FAW eggs and larval instars and plant growth stages are represented by different shapes and colours, respectively. Plant growth stages are categorised as mid (leaf and stem development/vegetative stage) or unspecified growth stages. FAW larval instars are classified as early instar (first & second), mid instar (third & fourth), mid-late instar (third-sixth), and late instar (fifth & sixth) stages.

3.3. Economic injury levels, economic thresholds, and action thresholds

We only identified EILs and ATs across various crop commodities in the literature, with the majority generated for maize and sorghum (Table 2). There were no ETs identified in our review. Most EILs and ATs have been established in the USA, with several also reported in South America and Africa (Table 2). Overall, we found significant variability in the manner EILs and ATs are reported, with a lack of consistency in pest pressure metrics, plant growth stages, and FAW life stages (Table 2). For sorghum, thresholds are generally higher at later plant growth stages, and are typically between 1 and 2 larvae per plant (Table 2). Soybeans are more susceptible to yield loss post-bloom than pre-bloom, warranting management intervention when a lower percentage of defoliation is observed (25% and 50%, respectively; Table 2). Interestingly, no action is warranted for FAW during vegetative stages of rice in Arkansas, as infestation is reported not to affect yield (Table 2). However, at the 5–6 tiller stage and the green ring plant growth stages, action is recommended when defoliation exceeds 50% and 20%, respectively (Table 2; Studebaker, 2021). For wheat, we found two ATs reported in the USA: the first recommends management intervention when 5–6 larvae per square foot is observed (Studebaker et al., 2016), and the second when windowpane injuries are observed in 25–30% of plants (Zukoff et al., 2019, Table 2). In peanuts, action is recommended when there are more than 4 larvae per foot within a row and 15% foliage loss is observed (Table 2). In cotton, action is recommended when 10–20 FAW are found per 100 plants (Table 2). Finally, in alfalfa and pasture and hay meadows, action is recommended when 2 or more FAW larvae per square foot is detected (Table 2). Drawing comparisons between ATs at various plant growth stages is difficult for maize, as these were reported as larvae/plant, larvae/part of plant (e.g. whorl), percentage infestation, percentage of injuries/damage observed, and percentage of defoliation (Table 2). Further, while plant growth stage is frequently specified, FAW life stage pertaining to the management thresholds reported/established is not (Table 2). This highlights a distinct lack of consistency in which management interventions have been established for this pest.

4. Discussion

The rapid and recent global invasion of FAW has led to an important need for knowledge surrounding its potential impact and effective management options. Here, we show a comprehensive assessment of available information on the yield loss caused by FAW globally. Given the broad range of commercial crops affected by FAW infestation, the compiled dataset will assist in the development of strategies to mitigate and manage the impact of FAW, particularly in recently invaded countries where knowledge gaps are largest. Our review of available FAW data revealed yield loss values for maize, sorghum, bermudagrass, rice, sweet corn, and cotton. However, empirical data on the effect of pest density on yield loss were only available for maize, sorghum, bermudagrass, and rice. Further, while various management thresholds (EILs, ETs, and ATs) have been reported across several crops, we found that in several scenarios the underlying data to support threshold development remain largely unknown.

Our analysis shows there is a disparity between experimentally derived yield loss and that obtained through farmer surveys or interviews, which is important for the future management of this pest. While most authors did not typically report on other pests in the studied system, yield losses, particularly those derived through self-reporting may be coincident with infestations or attacks by other pests, which can not only overinflate the perceived yield losses, but also overestimate the efficiency of management strategies (Willocquet et al., 2004). There is also a likely bias towards the over-reporting of crop losses in this instance due to loss-aversion (Kahneman et al., 1991). This was evident when looking at maize, where a clear difference in estimated mean losses caused by FAW was found between studies where yield loss was empirically derived compared with losses obtained through farmer surveys (Fig. 4). Experimentally derived yield losses may also be biased toward higher crop losses as they sought to establish the maximum yield losses that can occur as a result of FAW feeding. However, this may be counter balanced by the research priority of determining effective management strategies. There is likely an under-representation of non-English speaking countries in our review as we were less likely to capture reported yield losses and management interventions, in particular in FAW's native South American range, where publications and reports may be in Spanish or Portuguese. However, after consulting with a number of industry experts in Brazil to try and mitigate this bias, no further studies were identified other than those reported here.

Our review of the literature revealed a tendency by authors to focus on plant damage, rather than yield loss, likely due to the easier quantification of plant damage. Several FAW damage rating scales have been developed, with little standardisation across studies. For example, foliar damage under natural FAW infestation was quantified with a range of visual scores reflecting the perceived intensity of damage. The scoring system most widely used for a range of pests is the Davis scale, which rates the extent of leaf damage from 0 = no foliar damage (highly resistant) to 9 = severe foliar damage (totally susceptible) (Davis et al., 1992; Aguirre et al., 2016). However, with such a scale it is not possible to infer a direct yield loss, and multiple factors must be considered including the plant growth stage, larval instar, crop, and variety. A study conducted by Kuate et al. (2019) used a rating scale from 1 to 5 to score the severity of FAW damage on whorl-stage maize plants. However, the authors did not make an attempt to link this with yield loss. Damage scores must be used with caution to avoid overestimating economic impacts, as damage under certain thresholds or particular growth stages will not result in yield losses (Buntin, 1986; Trumble et al., 1993). For example, in rice grown in Arkansas, USA, FAW defoliation and infestation during vegetative stages does not result in any yield loss, which is reflected in the lack of threshold for FAW during this plant growth stage (Studebaker, 2021; Table 2). In addition, Britz (2020) found that the severity of larval damage to maize rated between 2 and 9 according on the Davis scale was not correlated with yield loss, further highlighting that the severity of damage symptoms is not an adequate indicator of how plants respond to damage, particularly when damage is incurred during early growth stages. While visual scores may be useful if they can be related back to yield loss, the two are not always correlated (e.g. Peairs and Saunders, 1981). Therefore, studies that solely utilise such scores without considering yield losses have limited use when trying to establish economic impacts. This is particularly relevant to the development of ETs and EILs, where accurate prediction of economic impacts without intervention are required.

We did not find any published data quantifying impacts for several major commodities known to be attacked by FAW, including wheat, soybeans, and chickpeas (Mello da Silva et al., 2017; Montezano et al., 2018; Machado et al., 2020), highlighting a knowledge gap. This is likely due to several reasons, including the minor, or sporadic impact of FAW in many reported hosts which has not warranted significant investment in research. While some studies have reported infestation levels and plant damage on several crops, yield loss is rarely quantified which obscures the true economic impact of FAW. Through this study, we also found a distinct lack of FAW yield loss data in Asia and the Pacific, particularly, China, Taiwan, Papua New Guinea, India, and south-east Asian countries, although this is likely due, at least in part, to its recent invasion within many of these countries.

The broad range of EILs and ATs determined for FAW across multiple crop commodities in different countries provides a valuable foundation from which to establish pest management guidelines. Thresholds derived from international data can be used to inform management guidelines for growers. Regionally calibrated thresholds require local field trials conducted to quantify the effect of specific environmental and ecological conditions. This approach was recently utilised in Australia following the invasion of the Russian wheat aphid (*Diuraphis noxia* Kurdjumov, 1913), where international ETs were utilised as an interim while thresholds were undergoing validation under Australian conditions and with Australian crop varieties (Ward et al., 2020). Indeed, much of the observed variation in thresholds is likely attributable to a lack of empirical data underpinning existing thresholds. For example, Huesing et al. (2018) highlights that in practice, true ETs and EILs have not been determined for most crops, with nominal ATs calculated based on expert opinion and experience, in combination with field scouting assessments. However, variation in EILs will also occur due to the variability in the parameters required to calculate EILs (i.e. pest management costs, market value of the commodity, and pest population controlled/proportion of injury reduction by tactic) between countries, and therefore reported EILs are not always directly transferable to other contexts. Further, we found the metrics used to report pest pressure were highly inconsistent (i.e. number of FAW per plant, percentage infestation, plant damage or defoliation), limiting our ability to compare studies. In future, improved standardisation of pest pressure metrics of FAW will support a more cohesive international research effort, where thresholds can be more easily related to environmental factors evident in different regions.

As the severity of FAW damage is strongly linked with larval growth stage (Linduska and Harrison, 1986; Britz, 2020), with later instars inflicting the most damage, the lack of knowledge surrounding the impacts of these later stages is of particular significance. Studies quantifying the relationship between pest pressure and yield loss with early larval instars (i.e. first and second instars), while useful, may not hold industry relevance given that leaf injury by early instar larvae is typically not visible, and therefore implementing control measures during these stages can be overlooked (Stern, 1973; Linduska and Harrison, 1986). The evident gap in the effect of late instar infestations on yield loss may be due to three main factors. Firstly, there is a greater emphasis on controlling earlier stages of FAW (Figs. 7–10) before mature, more damaging stages are reached. Secondly, later instars typically display cryptic feeding behaviours and are typically found feeding in deep protected areas of plants such as the whorl, leaf base/-collar, or fruit (Morrill and Greene, 1973). Finally, chemical control is not considered to be as effective at these late instars (Linduska and Harrison, 1986; Hardke et al., 2011), and therefore unless a systemic (or translaminar) insecticide is used, spray treatments may not be effective.

We also found limited data available on the economic impact of FAW on early plant growth stages, with the exception of rice. In maize, yield loss from FAW varies with plant growth stages (Buntin, 1986), and is typically most vulnerable to damage during seedling emergence, early-whorl stages, and also during the period of pre-tassel formation (Gross et al., 1982). The two most reported impacted crops, maize and sorghum, are typically planted in spring globally (Muchow et al., 1994; Sacks et al., 2010) and can therefore coincide with FAW population arrival in more temperate climates where winters do not allow continual persistence. Therefore, obtaining empirical data at the early emergence of these two crops in particular should be prioritised. Further, the percentage of infested maize plants during mid-vegetative growth stages is not a good predictor of eventual yield loss, suggesting that decisions surrounding insecticide applications should be based on the plant growth stages that require protection in addition to the infestation level observed (Britz, 2020).

Our literature review faced several limitations. We found that different contexts can alter the definition of "yield loss", with yield loss bearing different meanings that can include: (1) the potential yield loss in the field in the absence of management, (2) the actual yield loss in the field after management, and (3) the estimated or actual yield loss at an area, state, or country level, which includes areas where management strategies were either implemented or not. Generally, we found that experimentally derived yield losses (i.e. high confidence level) fell under the first two definitions, whereas farmer reported yield losses typically fell under the third, with limited empirical data capturing the actual yield loss when various management strategies were likely in place across a large scale. Our study also included yield losses derived across a range of different experimental contexts, each with experimental aims relating to specific (and often different) management applications, making direct comparisons difficult. In addition, we derived considerable data from studies that were established to test the efficacy of different insecticides against FAW, and we included the reported yield losses for some insecticides despite low efficacy. While some of the variability in experimental approaches has been accounted for by separating the reported crop loss data into different management strategies (i.e. maize: Fig. 5; sorghum: Fig. 6), we recognise caution is needed when interpreting our findings. Finally, we did not investigate differences between migratory or overwintering FAW populations on the intensity and duration of infestation, and if this translated to observed yield losses. While we chose not to investigate this as a large proportion of the yield loss data accumulated through our literature review experimentally manipulated FAW densities/pest pressure rather than relying on natural infestation rates, we recommend further research should be conducted to assess these effects.

Our findings point to the importance of sound empirical data to support the establishment of valid yield loss data and FAW pest management decisions. While we have identified global average yield losses resulting from FAW feeding, trials that generate regionally relevant yield loss data are required for recommendations that better consider local conditions affecting the cost-effectiveness of management interventions. Further, we recommend that a standardised pest pressure metric be developed to facilitate international consistency and comparison between studies, allowing a more coordinated global research effort in the management of FAW.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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