

Relationship between *Spodoptera frugiperda* (Lepidoptera: Noctuidae) damage and yield loss in maize

C Britz

 [orcid.org 0000-0002-1775-6192](https://orcid.org/0000-0002-1775-6192)

Dissertation accepted in fulfilment of the requirements for the degree *Master of Science in Environmental Sciences with Integrated Pest Management* at the North-West University

Supervisor: Prof J van den Berg

Co-supervisor: Prof MJ du Plessis

Assistant Supervisor: Dr A Erasmus

Graduation May 2020

29399645

PREFACE

This thesis was written and studies were conducted by C. Britz under the supervision of Prof J. van den Berg, H. Du Plessis (Unit for Environmental Sciences and Management, IPM program, North-West University, Potchefstroom, 2520, South Africa) and Dr A. Erasmus (Agricultural Research Council, Grain Crops, Private Bag X1251, Potchefstroom, 2520, South Africa). This thesis is submitted in fulfillment for the award of the degree of *Magister Scientiae* in *Environmental Science with IPM* of the North-West University.

ACKNOWLEDGEMENTS

Thank you to the North-West University for providing me with the opportunity to conduct my MSc degree in Unit of Environmental Sciences and Management within the IPM program and the Maize Trust which assisted in the experimental component of my project through funding.

Firstly, I want to express my gratitude to the ARC-Grain Crops Potchefstroom, the experiment farm in Malelane, and Nulandis Agricultural Research Station in Nelspruit and all the respective people involved: Dr Annemie Erasmus, Peter McKinnon and Fanus Swart as well as Willie Wentzel for setting aside a piece of land for my trials. I also want to thank Zander van Pletzen, Braam Ehlers, Piet Ramalema and Nipho Npila for their technical assistance during the last two years. I appreciate every warm welcome, cooperation and the assistance you have given me during this time.

Thank you to Dr Annemie Erasmus for all the trouble you went through with trial planning, arranging for workers to assist me during harvests and for assisting me during diet preparation. Furthermore, I want to thank Carina Kotze, a fellow student, who assisted me with the trials conducted in Chapter 5.

Last but not least, I want to give special thanks to both my supervisors, Prof Johnnie van den Berg and Prof Hannalene Du Plessis, for all their advice, guidance, support and motivation during the last two years. I am grateful for all their help with my statistics and for their assistance with my trial design. A special thanks to Prof Johnnie for all the guidance he provided to me with my Nelspruit trials. Thank you for the trouble of reviewing and editing my chapters. I appreciate everything you went through to ensure that my project was a success.

TABLE OF CONTENTS

PREFACE.....	ii
TABLE OF CONTENTS.....	iv
ABSTRACT.....	vii
Chapter 1.....	1
INTRODUCTION.....	1
1.1 Background to the study.....	1
1.2 Problem statement and justification.....	2
1.3 Study objectives.....	3
1.3.1 Main objective.....	3
1.3.2 Specific objectives.....	3
1.3.3 Hypotheses.....	3
1.4 References.....	4
Chapter 2.....	8
LITERATURE REVIEW.....	8
2.1 Background.....	8
2.2 <i>Spodoptera frugiperda</i> ecology and biology and pest status.....	8
2.3 Population dynamics of <i>S. frugiperda</i>	9
2.4 The concept of yield and yield loss.....	10
2.5 Plant response to pest injury.....	11
2.6 Plant response to FAW damage.....	12
2.7 Plant injury and plant damage.....	14
2.8 Yield loss data.....	14
2.9 Integrated pest management.....	15
2.10 Economic threshold level.....	16
2.11 Economic injury level.....	17
2.12 Action threshold level.....	18
2.13 Chemical control.....	19
2.13.1 Neuromuscular insecticides.....	20
2.13.2 Acetylcholinesterase (AChE) inhibitors.....	20
2.13.3 Sodium channel modulators.....	21
2.13.4 Natural insecticides.....	21
2.13.5 How insecticides enter the body of an insect.....	22
2.14 Host plant resistance.....	22
2.15 Cultural control.....	23

2.16 Biological control	24
2.17 People's perceptions of the importance of FAW	25
2.18 Structure of thesis	25
2.19 References	26
Chapter 3.....	38
The effect of different levels of infestation and plant growth stage at infestation on yield loss caused by <i>Spodoptera frugiperda</i> in South Africa	38
3.1 Introduction	39
3.2 Materials and methods	41
3.2.2 Rearing of <i>Spodoptera frugiperda</i>	41
3.2.3 Field Trial 1: The relationship between infestation level (% incidence) of damaged plants) and yield	42
3.2.4 Trial 2: The effect of plant growth stage and time of inoculation on yield loss	45
3.2.5 Trial 3: The effect of different levels of FAW infestation and insecticide application on yield.....	46
3.2.6 Data analysis.....	47
3.3 Results and discussion	48
The relationship between severity of damage symptoms and yield loss per plant	48
3.3.1 Field Trial 1: The relationship between infestation level (incidence (%) of damaged plants) and yield	51
3.3.2 Trial 2: The effect of plant growth stage at time of inoculation on yield loss.....	53
3.3.3 Trial 3: The effect of different levels of FAW infestation and insecticide application on yield.....	57
3.4 Conclusions	60
3.5 References	60
Chapter 4.....	65
The effect of protection of maize plants during certain growth stages on yield losses caused by <i>Spodoptera frugiperda</i>	65
4.1 Introduction	66
4.2 Materials and methods	68
4.2.1 Trials 1 and 2	68
4.2.2. Trial 3	69
4.2.3 Insecticide spray schedule.....	70
4.2.4 Data collection	71
4.2.5 Data analysis.....	71
4.3 Results	71

4.3.1 Trial 1	71
4.3.2 Trial 2	74
4.3.3 Trial 3	75
4.4 Discussion.....	78
4.4.1 Trials 1 and 2	78
4.4.2 Trial 3	78
4.5 Conclusion	79
4.6 References	80
Chapter 5.....	84
Efficacy of granular insecticides for control of <i>Spodoptera frugiperda</i> in maize whorls	84
Abstract.....	84
5.1 Introduction.....	85
5.2 Materials and methods	86
5.2.1 Larval rearing.....	86
5.2.2 Field trial	86
5.2.3 Laboratory trial.....	87
5.2.4 Data analyses	88
5.3 Results and discussion.....	89
5.3.1 Field trial	89
5.3.2 Laboratory trial.....	90
5.4 Conclusion	91
5.5 References	91
Chapter 6.....	96
Conclusion and recommendations	96
6.1 Conclusion	96
6.2 Recommendations.....	98
6.3 References	99

ABSTRACT

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) feeding on maize results in extensive foliar damage if plants are attacked during the pre-flowering stages. Infestation during late plant growth stages results in ear damage. Insecticide application is the most common method of FAW control and is extensively applied in some farming systems and often without any consideration of infestation levels or estimated yield losses. While some information on FAW infestation and yield loss are available from South American studies, little information is available on the relationship between infestation level, severity of damage and plant response to injury in Africa. Decisions to apply insecticides for FAW control should be based on infestation levels, expected yield losses and cost of control. The lack of data on infestation levels and yield loss, plant growth at time of infestation and insecticide application, and relationship between severity of damage and yield loss were addressed in this study. This study also investigated the efficacy of granular insecticide formulations, to address the poor levels of control of FAW larvae inside plant whorls that are generally reported for spray applications. Field trials were conducted at different localities and under either natural or artificial infestation. Treatments in the various trials consisted of spray applications at different plant growth stages to keep plants pest-free for certain periods of time, infestations at different plant growth stages, and studies on the relationship between the degree of leaf damage, determined on a 1 – 9 scale, and yield. A laboratory as well as a field trial were conducted to evaluate the efficacy of granular formulations applied into plant whorls. Granular insecticides used were: spinosad SC, beta-cyfluthrin GR, carbaryl GR and a diatomaceous formulation. Insecticide applications during the V7-growth stage, four to five weeks after seedling emergence, resulted in the highest yield gain. The degree of damage to plants did not correlate strongly with yield and yield loss but was strongly dependent on the plant's growth stage. Yield losses increased with increased incidence of infested plants per plot. The largest yield gains were obtained in plots where protection was implemented when 30 – 60% of plants were infested. Plots that remained unprotected during the three field trials suffered yield losses of 41.9, 26.5 and 56.8%, respectively. Yield gains were not significantly higher in any treatments that received more than three insecticide applications. Yield was higher in plots that received protection during early vegetative stages compared to protection during later growth stages. Granular insecticides were not as effective as the foliar spray application and larval mortality ranged between 2.5% (carbaryl GR) and 87.5% (beta-cyfluthrin GR). Spinosad dust and beta-cyfluthrin were effective in controlling FAW larvae but only under laboratory conditions. Granular insecticide formulations can be used by small scale farmers as an alternative control measure against FAW.

Keywords: Damage severity; Economic threshold level; Granular insecticides; Insecticide application; Leaf damage

Chapter 1

INTRODUCTION

1.1 Background to the study

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is native to the tropical and subtropical regions of the Americas, with geographical confinement during winter seasons to South Florida and Texas in North America (Hogg *et al.* 1982; Jamjanya 1987; Hernandez-Mendoza *et al.* 2008; Nagoshi and Meagher 2008; Nagoshi *et al.* 2009, 2017) and large parts of tropical South America. This pest is adapted to warm climatic conditions that enable it to complete its life cycle in a short period, thereby producing several generations per cropping season, in addition to the fact that it does not undergo diapause (Jamjanya 1987; Luginbill 1928; Flanders *et al.* 2017; Kumela *et al.* 2018). These biological traits of FAW enable maximum damage infliction and yield loss per season (Jamjanya 1987; FAO 2018; Prasanna *et al.* 2018).

Spodoptera frugiperda is an invasive pest species in Africa. It was first reported in 2016 in Western and Central Africa (Goergen *et al.* 2016) and in 2017 in South Africa (Jacobs *et al.* 2018). It is a serious pest on graminaceous plant species which include many crops of agricultural importance (Buntin 1986; Goergen *et al.* 2016). Although the wide host plant range of FAW increases its pest status, it is most commonly observed in maize cropping systems (Buntin 1986; Hernandez-Mendoza *et al.* 2008; Midega *et al.* 2018).

Spodoptera frugiperda is now widespread throughout Africa (Early *et al.* 2018; Prasanna *et al.* 2018) and was recently reported in Egypt (FAO 2019). Modelling of the distribution of FAW in Africa showed that it will become endemic in most parts of sub-Saharan Africa (Early *et al.* 2018) and that migration to the southern most areas of the continent could also occur (Du Plessis *et al.* 2018). This pest threatens the production of maize (Hruska and Gould 1997; FAO 2018; Kumela *et al.* 2018), which is the main staple food on the continent. Maize provides half of the calories consumed daily in the Southern Africa diets (Day *et al.* 2017). Effective pest management in small holder agricultural systems is essential to ensure sustainable food production (Lima *et al.* 2010; Day *et al.* 2017; Kumela *et al.* 2018). Contrary to commercial farming systems which are economically driven (Perrin 1997; Oerke and Dehne 2004), subsistence farmers are dependent on their harvest for food security (Day *et al.* 2017; Kumela *et al.* 2018; Midega *et al.* 2018).

Insufficient knowledge about the phenology and injuriousness of FAW and lack of appropriate management strategies in Africa contribute to uncertainty with regards to its management. For example, little information exists on the relationships between the time and level of infestation and yield loss, when to apply pesticides and the general economics of FAW control from Africa. These uncertainties may either contribute to unnecessary pesticide applications, or inaction which may result in economic losses (Day *et al.* 2017; Prasanna *et al.* 2018).

1.2 Problem statement and justification

Although the pest status of FAW varies between regions and over seasons, it is often controlled by means of chemical pesticide applications (Lima *et al.* 2010). For chemical control to be economical, it must be applied according to appropriate economic threshold levels (ETLs), based on the incidence of damaged plants as well as severity of damage (Hruska and Gladstone 1988; Vincent *et al.* 2003; Petrovskii *et al.* 2014a, b). Unfortunately, very little literature is available on the relationships between FAW infestation, degree of damage and yield loss of maize. Furthermore, literature that does address this pest damage–yield loss relationship shows poor correlations. Studies conducted in South America indicated large variation in plant response to injury, for example, yield losses of 45% (Hruska and Gladstone 1988) and 18% (Cruz and Turpin 1983) was reported on maize fields in which 100% of the plants were infested by FAW. Baudron *et al.* (2019) recently estimated a 12% yield reduction from FAW damage to maize in Eastern Zimbabwe, which is also the only yield loss estimate calculated under actual farming conditions in Africa. Hruska (2019), in a review on this topic, reported that maize yield losses never exceeded 15% at defoliation rates of 70, 24 or 50%. At a defoliation rate of 25%, yield losses of between 5 and 9% were reported, indicating the ability of maize plants to compensate for damage or to tolerate leaf injury.

Available literature on the injuriousness of FAW to maize and associated yield losses from South America is nearly all from the pre-1990 publications and can therefore be considered dated. Unfortunately, other than these (Wiseman *et al.* 1967; Morrill and Greene 1974; Van Huis 1981; Harrison 1984; Buntin 1986; Andrews 1988; Hruska and Gould 1997), not many recent yield loss studies have been conducted and those pre-1990 published studies on plant response to damage are not very applicable to African farming conditions and climate. Reports on yield losses in Africa are limited to a few recent papers, farm survey reports and yield loss assessments under uncontrolled natural infestations (Kumela *et al.* 2018; Midega *et al.* 2018; Baudron *et al.* 2019; Hruska 2019; Kuate *et al.* 2019; Sisay *et al.* 2019).

Recent estimates of the cost of control of FAW on maize in Africa indicate a value of US\$ 7.88/ha (Hruska 2019). To be economically profitable, farmers should not spend more than this amount on FAW control, and yield loss should also not exceed this amount (which is approximately 15% of the yield on a field that yields 1,400 kg/ha). For a single insecticide application against FAW, a farmer should therefore not spend more than US\$ 7.88/ha under general African farming conditions (Hruska 2019). The low prices received by the farmers and low productivity result in very limited options for smallholder farmers to manage FAW in their maize (Hruska 2019). This further complicates decision making regarding chemical control and highlights the need for data on the relationships between pest damage, infestation levels and yield loss. Most of the literature on these topics is from North and South America, with no data generated yet in Africa. Locally generated data on the relationship between FAW damage and yield loss in maize will contribute to decision support systems and development of guidelines for control of the pest in South Africa.

1.3 Study objectives

1.3.1 Main objective

The main objective of the study was to determine the relationship between the severity of *S. frugiperda* damage to the whorl leaves of maize plants and the actual yield loss, and to determine the effects of pesticide application on plant response to damage.

1.3.2 Specific objectives

Specific objectives were to:

- i. determine the correlation between foliar damage caused by FAW larvae and yield loss of maize plants;
- ii. estimate the optimal time of insecticide application, based on maize growth stage and level of foliar damage; and
- iii. determine the efficacy of granular and dust formulations of insecticides applied directly into the whorl of maize plants for control of FAW larvae.

1.3.3 Hypotheses

- i. It is expected that application of insecticides at different growth stages will result in different levels of protection against FAW damage.

- ii. It is expected that insecticide applications at earlier plant growth stages will result in better protection against the FAW than insecticides applied at later plant growth stages.
- iii. It is expected that granular insecticides will provide improved control compared to foliar applied insecticides due to their more preferable application method.

1.4 References

- ANDREWS, K.L. 1988. Latin American research on *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *The Florida Entomologist* 71: 630-653.
- BAUDRON, F., ZAMAN-ALLAH, M.A., CHAIPA, I., CHARI, N. and CHINWADA, P. 2019. Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* JE Smith) damage in African smallholder maize fields and quantifying its impact on yield: a case study in eastern Zimbabwe. *Crop Protection* 120: 141-150.
- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- CRUZ, I. and TURPIN, F.T. 1983. Yield impact of larval infestations of the fall armyworm (Lepidoptera: Noctuidae) to midwhorl growth stage of corn. *Journal of Economic Entomology* 76:1052–1054.
- DAY, R., ABRAHAMS, P., BATEMAN, M., BEALE, T., CLOTTEY, V., COCK, M., COLMENAREZ, Y., CORNIANI, N., EARLY, R., GODWIN, J., GOMEZ, J., MORENO, P.G., MURPHY, S.T., OPPONG-MENSAH, B., PHIRL, N., PRATT, C., SILVESTRI, S. and WITT, A. 2017. Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management* 196-201.
- DU PLESSIS, H., VAN DEN BERG, J., OTA, N. and KRITICOS, D.J. 2018. *Spodoptera frugiperda*. *CSIROInSTePP Pest Geography* 1-7.
- EARLY, R., GONZALEZ-MORENO, P., MURPHY, S.T. and DAY, R. 2018. Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm. *NeoBiota* 40: 25-50. <https://doi.org/10.3897/neobiota.40.28165>.
- FAO. 2019. Food and Agricultural Organization. FAO and MALR resuming efforts to face fall armyworm (FAW) infestation in Egypt. FAO in Egypt. <http://www.fao.org/egypt/news/detail-events/en/c/1195461/> (accessed 01 July 2019).

- FAO. 2018. Food and Agricultural Organization. Integrated management of the fall armyworm on maize: A guide for Farmer Field Schools in Africa. FAO. Rome. Italy.
- FLANDERS, K.L., BALL, D.M. and COBB, P.P. 2017. Management of FAW in pastures and hay fields. The Alabama Cooperative Extension System (Alabama A&M University and Auburn University). Pp. 8.
- GOERGEN, G., KUMAR, P.L., SANKUNG, S.B., TOGOLA, A. and TAMO, M. 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in west and central Africa. *PLoS ONE*. DOI: 10.1371/journal.pone.0165632.
- HARRISON, F.P. 1984. The development of an economic injury level for low populations of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 67: 335-339.
- HERNANDEZ-MENDOZA, J.L., LOPEZ-BARBOSA, E.C., GARZA-GONZALEZ, E. and MAYEK-PEREZ, N. 2008. Spatial distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize landraces grown in Colima, Mexico. *International Journal of Tropical Insect Science* 28: 126-129.
- HOGG, D.B., PITRE, H.N. and ANDERSON, R.E. 1982. Assessment of early-season phenology of the fall armyworm (Lepidoptera: Noctuidae) in Mississippi. *Environmental Entomology* 11: 705-710.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CAB Reviews* 14: 1-11.
- HRUSKA, A.J. and GLADSTONE, S.M. 1988. Effect of period and level of infestation of the fall armyworm, *Spodoptera frugiperda*, on irrigated maize yield. *The Florida Entomologist* 71: 249-254.
- HRUSKA, A.J. and GOULD, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology* 90: 611-622.
- JACOBS, A., VAN VUUREN, A. and RONG, I.H. 2018. Characterisation of the fall armyworm (*Spodoptera frugiperda* J.E. Smith) (Lepidoptera: Noctuidae) from South Africa. *African Entomology* 26: 45-49.
- JAMJANYA, T. 1987. Consumption, utilization, biology, and economic injury level of fall armyworm, *Spodoptera frugiperda* (J.E. Smith), on selected Bermudagrasses. LSU

Historical Dissertations and Theses. 4362. https://digitalcommons.lsu.edu/gradschool_disstheses/4362

- KUATE, A.F., HANNA R., DOUMTSOP FOTIO, A.R.P., ABANG, A.F., NANGA, S.N., NGATAT, S., TINDO, M., MASSO, C., NDEMAH, R., SUH, C. and FIABOE, K.K.M. 2019. *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Cameroon: Case study on its distribution, damage, pesticide use, genetic differentiation and host plants. *PLoS ONE* 14: e0215749. <https://doi.org/10.1371/journal.pone.0215749>
- KUMELA, T., SIMIYU, J., SISAY, B., LIKHAYO, P., MENDESIL, E., GOHOLE, L. and TEFERA, T. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management* 65: 1-9.
- LIMA, M.S., SILVA, P.S.L., OLIVEIRA, O.F., SILVA, K.M.B. and FREITAS, F.C.L. 2010. Corn yield response to weed and fall armyworm controls. *Planta Daninha, Viscosa-MG* 28: 103-111.
- LUGINBILL, P. 1928. The Fall Armyworm. *USDA Technical Bulletin* 34: 91 pp.
- MIDEGA, C.A.O., PITTCHAR, J.O., PICKETT, J.A., HAILU, G.W. and KHAN, Z.R. 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J.E. Smith), in maize in East Africa. *Crop Protection* 105: 10-15.
- MORRIL, W.L. and GREENE, G.L. 1974. Survival of fall armyworm larvae and yields of field corn after artificial infestations. *Journal of Economic Entomology* 67: 119-123.
- NAGOSHI, R.N. and MEAGHER, R.L. 2008. Review of fall armyworm (Lepidoptera: Noctuidae) genetic complexity and migration. *The Florida Entomologist* 91: 546-554.
- NAGOSHI, R.N., FLEISCHER, S., MEAGHER, R.L., HAY-ROE, M., KHAN, A. and MURUA, M.G. 2017. Fall armyworm migration across the Lesser Antilles and the potential for genetic exchanges between North and South American populations. *PLoS ONE* 12: e0171743. doi:10.1371/journal.pone.0171743
- NAGOSHI, R.N., FLEISCHER, S., and MEAGHER, R.L. 2009. Texas is the overwintering source of fall armyworm in Central Pennsylvania: Implications for migration into the North-eastern United States. *Environmental Entomology* 38: 1546-1554.
- OERKE, E.-C. and DEHNE, H.-W. 2004. Safeguarding production – losses in major crops and the role of crop protection. *Crop Protection* 23: 275-285.

- PERRIN, R.M. 1997. Crop protection: taking stock for the new millennium. *Crop Protection* 16: 449-456.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014a. Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks. *Physics of Life Reviews* 11: 467-525.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014b. Multiscale ecology of agroecosystems is an emerging research field that can provide a stronger theoretical background for the integrated pest management. Reply to comments on "Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks". *Physics of Life Reviews* 11: 536-539.
- PRASANNA, B.M., HUESING, J.E., EDDY, R. and PESCHKE, V.M. (eds). 2018. Fall armyworm in Africa: A guide for integrated pest management, First Edition. Mexico, CDMX: CIMMYT.
- SISAY, B., TEFERA, T., WAKGARI, M., AYALEW, G. and MENDESIL, E. 2019. The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda*, in maize. *Insects* 10: 45.
- VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.
- VINCENT, C., HALLMAN, G., PANNETON, B. and FLEURAT-LESSARD, F. 2003. Management of agricultural insects with physical control methods. *Annual Review of Entomology* 48: 261-81.
- WISEMAN, B.R., WASSOM, C.E. and PAINTER, R.H. 1967. An unusual feeding habit to measure differences in damage to 81 Latin-american lines of corn by the fall armyworm, *Spodoptera frugiperda* (J. E. Smith). *Agronomy Journal* 59: 279-281.

Chapter 2

LITERATURE REVIEW

2.1 Background

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a widespread polyphagous pest (Montezano *et al.* 2018) which attacks many poaceous crops (Buntin 1986; Goergen *et al.* 2016; Prasanna *et al.* 2018). The fall armyworm is indigenous to the tropical regions of Central and North America (Hogg *et al.* 1982; Jamjanya 1987; Hernandez-Mendoza *et al.* 2008; Goergen *et al.* 2016; Du Plessis *et al.* 2018; Early *et al.* 2018). During cold winter seasons in North America, FAW's biological requirements limits its distribution range to South Florida and Texas (Hogg *et al.* 1982; Jamjanya 1987; Hernandez-Mendoza *et al.* 2008; Kumela *et al.* 2018; Garcia *et al.* 2018). FAW occurs widely in the northern regions of South America where the tropical climate allows for year-round persistence and growing of host crops (Luginbill 1928).

Spodoptera frugiperda is an invasive pest species in Africa. The first record of FAW presence in South Africa was in 2017 (Jacobs *et al.* 2018), one year after it was reported in West and Central Africa (Goergen *et al.* 2016).

2.2 *Spodoptera frugiperda* ecology and biology and pest status

The life cycle of FAW, from egg to moth, can be completed within 30 days under favourable climatic conditions (Buntin 1986). In regions where FAW is endemic, a continuous cycle is observed, contrary to that in colder regions with less favourable environmental conditions where FAW either becomes locally extinct or show migratory behaviour (Hogg *et al.* 1982; Buntin 1986; Hernandez-Mendoza *et al.* 2008). Furthermore, the ability of moths to fly distances of up to 100 km in a single night, assisted by air currents, contributes to FAW's vast geographical distribution (Midega *et al.* 2018; Early *et al.* 2018). In North America, spread occurs through migration of moths in a northern direction or via exportation of infested crop material (Hogg *et al.* 1982; Buntin 1986). In the presence of optimal wind currents, moths are able to cover vast geographic areas, with distances of up to 1600 km in only 30 hours (Rose *et al.* 1975; Hogg *et al.* 1982). This potential of FAW moths to migrate vast distances contributes to its pest status and provide challenges to its management in Africa.

2.3 Population dynamics of *S. frugiperda*

The warm climate in most of Africa is suitable for rapid development and reproduction of FAW, which aggravates its pest status by allowing persistence of pest populations in certain regions, similar to those in the Americas (Buntin 1986; Hernandez-Mendoza *et al.* 2008; Du Plessis *et al.* 2018; Early *et al.* 2018) (Fig. 2.1). In addition to the suitable climate, certain agricultural practices also contribute in creating a favourable environment for FAW populations to persist throughout the year in most African regions (Prasanna *et al.* 2018).

Distribution patterns of larvae within the cropping system are determined by the ovipositional preference of female moths which lay their eggs on younger maize leaves to allow for neonate larvae to feed on these soft, nutritious leaves (Morrill and Greene 1973; Buntin 1986; Linduska and Harrison 1986; Sadek 2011). Larvae then move downwards into the protective whorl of the maize plant where they feed up to the last instar (Morrill and Greene 1973; Buntin 1986; Linduska and Harrison 1986; Stapel *et al.* 1998; Sadek 2011). The pupal stage is completed in the soil from which moths then emerge.

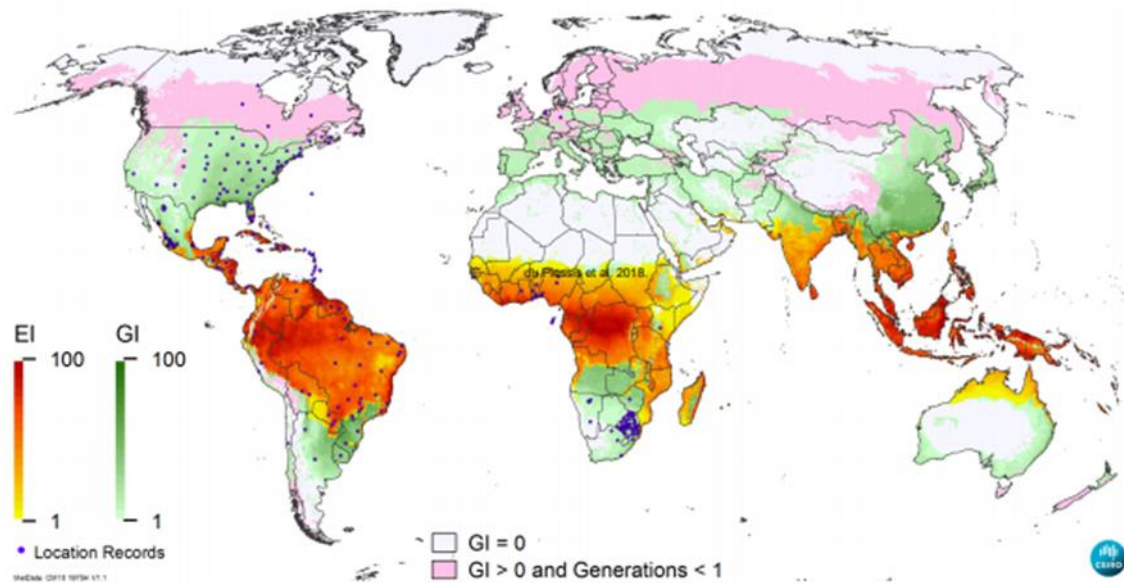


Figure 2.1. Distribution map of the FAW indicating areas with suitable ecoclimatic indices that allow permanent establishment of the pest. EI = ecoclimatic index; GI = Growth index (Du Plessis *et al.* 2018).

Population dynamics of species fluctuate along an equilibrium, directly influenced by environmental as well as physiological and behavioural factors across seasons (Buntin 1986; Hernandez-Mendoza *et al.* 2008; Laborda *et al.* 2015; Baldacchino *et al.* 2017). Temperature has the greatest impact on community structure and stability of pest populations and affects their interactions with all living species within the habitat (Damos and Soulopoulou 2015).

Increasing temperatures in the Southern African region creates favourable conditions for insects to flourish which make them less manageable.

2.4 The concept of yield and yield loss

Prasanna *et al.* (2018) stated that commercial farmers are dependent on seed companies to continuously supply them with high quality crop seeds that are abundantly available throughout the planting season to produce maximum attainable yields (Fig. 2.2). This level of support is not available for small holder farmers in Africa, making them particularly vulnerable to pest attack and other biotic and abiotic constraints that affect crop production (Hruska 2019).

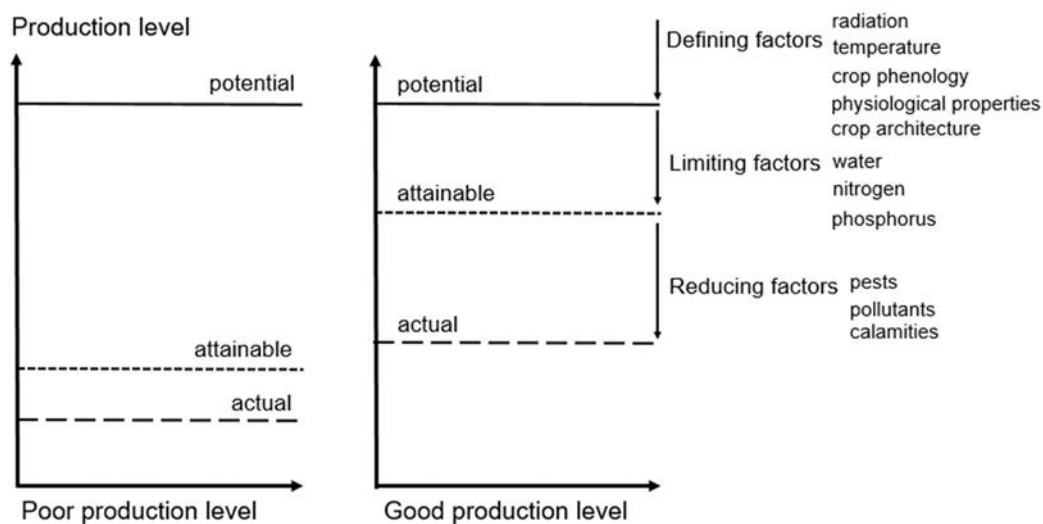


Figure 2.2. The different levels of yield production with the biotic as well as abiotic factors that influence it (Rossing and Heong 1997).

All biotic and abiotic factors contribute to the quantity as well as the quality of the end product (Bardner and Fletcher 1974; Buntin 1986; Lima *et al.* 2010). Potential yield can only be obtained in a perfect growing season if all factors are favourable with no crop loss (Fig. 2.2), but it is highly unrealistic to expect to attain such yields. The yield obtained in cropping systems under excellent management and pest control is defined as attainable yield, which is lower than the potential yield, due to factors that cannot be managed (Rossing and Heong 1997). Lastly, actual yield is the physical yield obtained that is of high enough quality to be sold. Both the attainable and actual yield are not necessarily economically desirable but incorporating

IPM strategies based on the ETLs of pest species aims to reduce the yield gaps (Rossing and Heong 1997).

2.5 Plant response to pest injury

The generalized response curve (Fig. 2.3) indicates the quantitative effect on yield production levels at different pest population densities (Bardner and Fletcher 1974). Theoretically, this relationship is linear, which suggests that pest population numbers are positively correlated to the degree of damage they cause and negatively correlated with yield. However, in practice it is not as simple and the line that describes the relationship between pest damage and crop yield is curvilinear with plateaus at very low and high population densities, and a linear relationship at moderate population densities (Bardner and Fletcher 1974).

This yield response curve consists of five important phases which represent the nature of the pest population dynamics within each phase (Fig. 2.3). These phases comprise the upper level, compensation, linear response, competition and lower level (Bardner and Fletcher 1974). The response curve also indicates a point (threshold) at which measurable yield loss starts to occur. This enhances the understanding of the relationship between damage symptom severity and degree of yield loss and its correlation to pest population densities relative to the threshold (Bardner and Fletcher 1974).

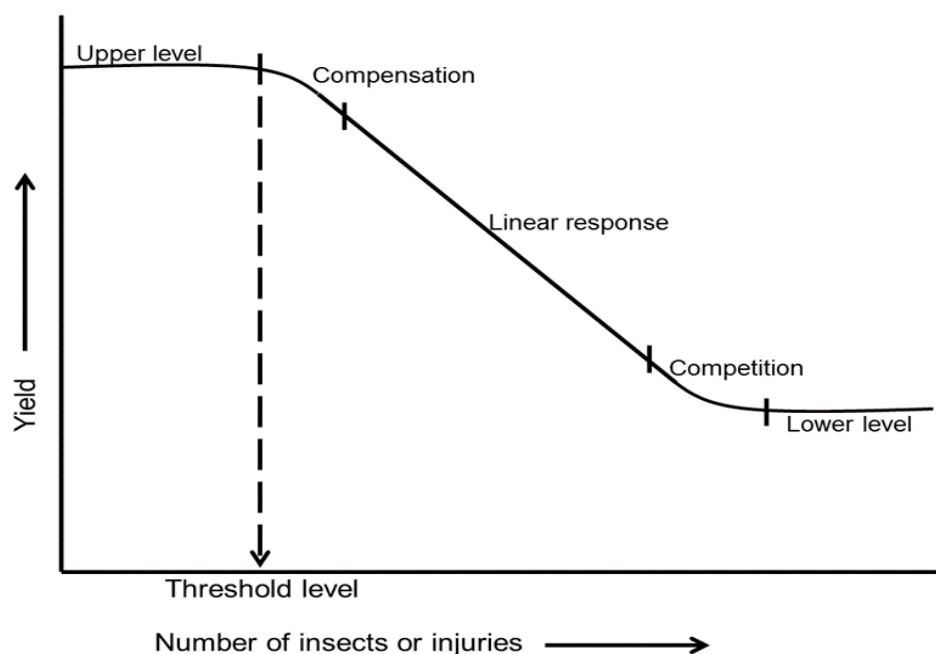


Figure 2.3. Diagram indicating the generalised response curve which describes the effect of pest population density on quantitative yield production (Bardner and Fletcher 1974).

The upper level of the response curve indicates relatively low to no levels of damage due to pest population density being below the “threshold” where loss can be measured (Bardner and Fletcher 1974). High tolerance or resistance levels, due to antixenosis or antibiosis, in addition to mechanical and chemical defence mechanisms, reduce and tolerate the effects of pest damage (Bardner and Fletcher 1974; Buntin 1986). Therefore, such low population densities of the pest, which lie below the threshold level, have no negative impact on the overall quantity or quality of the crops and its yield (Bardner and Fletcher 1974). However, once the infestation level increases above a certain level, the response curve moves into a linear phase (Bardner and Fletcher 1974).

An “arms-race” between the pest species and the crop can be observed, where population dynamics of both the pest and crop fluctuate along the linear regression line, resulting in increasing yield loss at a constant rate (Bardner and Fletcher 1974) until it levels off and increased numbers of pest individuals do not have an increased adverse effect on the crop.

The levelling-off indicated on the response curve can be explained by the survival of the fittest theory (Bardner and Fletcher 1974). Most of the preferred resources, such as the soft leaves and leaf sap, are already exploited and only the tougher plant tissues which are less nutritious remain. At the lower level of the damage curve, increased numbers of pest individuals do not contribute to further crop damage. At the latter phase, maximum severity of damage that the crop can tolerate is reached, therefore making the injury level independent from the pest density, which is indicated by the plateau. Theoretically, pest population numbers should increase resulting in no further damage; however, in practice, due to the extensive damage and depletion of most of the nutrients, the pest may move to another more suitable crop (Bardner and Fletcher 1974).

2.6 Plant response to FAW damage

The susceptibility of plants to pest injury and subsequent yield loss are highly dependent on the complexity of their interactions as well as the biotic and abiotic factors in the community (Buntin 1986; Lima *et al.* 2010; Harrison *et al.* 2019). The genetic composition of host plants plays an important role in their response to herbivory (Headley 1979; Wiseman *et al.* 1994). Plants require a balance between optimal temperature as well as soil moisture and nutrients, as well as the absence of pests to produce maximum yield (Lima *et al.* 2010). However, the conditions that favour plant growth are also usually favourable for pest establishment and development (Lima *et al.* 2010). A trade-off exists for the host plant between producing an optimal yield and defending itself against pests and diseases (Buntin 1986; Lima *et al.* 2010). Therefore, the interactions among host plants and herbivorous pests are directly influenced

by the environmental conditions that form part of the pest and 'disease triangle' (Buntin 1986; Agrios 2005). However, in epidemiology, a fourth component, time, is added to this triangle (Agrios 2005). Time plays a vital role in every step of this cycle, where the level of crop damage is directly related to the feeding period and pest density within the cropping system (Linduska and Harrison 1986; Agrios 2005; Flanders *et al.* 2017).

Cultural control measures are implemented based on time manipulation to reduce the overlapping period of the susceptible growth stages of hosts and the damage-inflicting stage of pests (Van Emden 1983; Agrios 2005). Furthermore, the period of favourable or unfavourable environmental conditions determines the rate of pest development and therefore the number of generations that would be able to infest their hosts as well as the number of offspring produced (Luginbill 1928; Jamjanya 1987; Early *et al.* 2018). Thus, if the environmental conditions are optimal for FAW development, moths will lay their eggs on young maize plants during the first few weeks following seedling emergence, to allow for larvae to feed on soft leaf tissue of young plants, which subsequently results in maximum damage infliction (Jamjanya 1987). These environmental factors have a direct influence on the strength and dynamics of the interactions between pests and host crops and determine the severity of foliar damage and ultimately yield loss of maize as a result of injuries caused by FAW larvae (Buntin 1986; Linduska and Harrison 1986; Flanders *et al.* 2017).

Fall armyworm damage to maize results in both primary and secondary crop losses (Morrill and Greene 1974; Lima *et al.* 2010; Flanders *et al.* 2017; Soper *et al.* 2018). Direct damage to the basal region of maize ears, kernels, or the growth points of maize plants results in primary loss (Serra and Trumper 2006; Hernandez-Mendoza *et al.* 2008; Lima *et al.* 2010; Soper *et al.* 2018). Secondary losses are defined as the extensive reduction of leaf material, in addition to architectural damage that alter the physiological ability of the maize plant to transport nutrients or to photosynthesize (Serra and Trumper 2006; Hernandez-Mendoza *et al.* 2008; Lima *et al.* 2010; Soper *et al.* 2018).

The severity of FAW damage to plants correlates strongly with larval growth stage (Linduska and Harrison 1986; Flanders *et al.* 2017). Leaf damage that results from first-instar larval feeding is negligible and damage caused by these larvae does not contribute to yield loss. Early-instar larvae require very little nutrients and become cannibalistic as they develop into later-instars, which results in a rapid decrease in their numbers on a plant (Hernandez-Mendoza *et al.* 2008; Flanders *et al.* 2017) The proportional leaf surface area consumed by a single larvae of different instars are indicated in Figure 2.4. Leaf injury inflicted by first and second instar larva is not visible to farmers and therefore, no control measures are implemented during this early stage (Stern 1973; Linduska and Harrison 1986). The level of

injury increases exponentially after each moulting (Flanders *et al.* 2017). Foliar damage caused by fourth, fifth and sixth-instar larvae is extensive and clearly visible inside the whorls of infested maize plants (Fig. 2.4) (Linduska and Harrison 1986; Flanders *et al.* 2017). Linduska and Harrison (1986) indicated that a 6th instar larva consumes more leaf material than all other instars together.

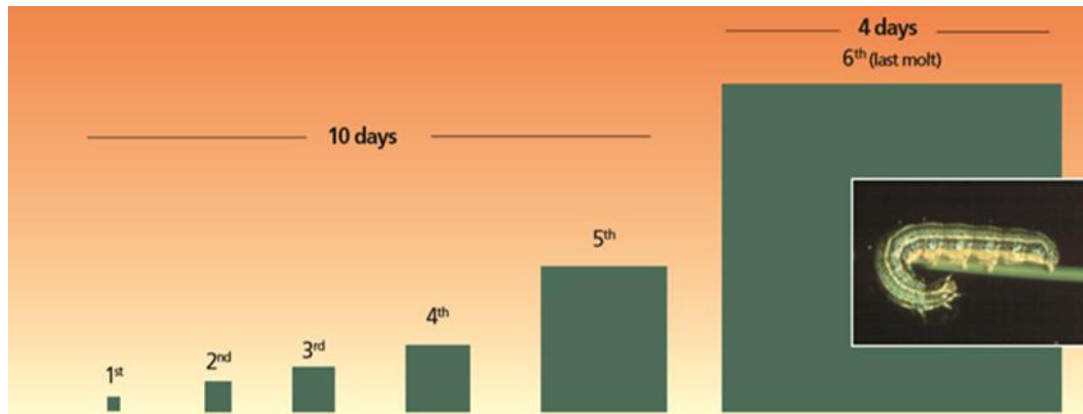


Figure 2.4. Estimated quantity of leaf material consumed per larval instar and relative duration of FAW larval feeding periods of different instars (Flanders *et al.* 2017).

2.7 Plant injury and plant damage

According to Fenemore (1982) and Pedigo *et al.* (1986), it is important to differentiate between plant injury and plant damage when decisions are made regarding implementation of control measures (Stern *et al.* 1959; Buntin 1986; Pedigo 2004). Pests cause different levels of injury to plants, depending on their developmental stage, environmental conditions and the host suitability of specific cultivars (Buntin 1986). Injury to plants is defined as any negative impact that a pest species has on general plant health. Injury can therefore be tolerated by a plant, preventing or limiting any measurable yield losses (Buntin 1986). Plant damage occurs once a pest inflicts a degree of injury higher than what the plant can tolerate, which then results in measurable loss, that can be classified as quantitative or qualitative yield loss (Bardner and Fletcher 1974; Buntin 1986).

2.8 Yield loss data

Yield losses due to FAW in maize have been reported to be between 30% and 70% in Latin America (Van Huis 1981; Hruska and Gould 1997; Lima *et al.* 2010; Aguirre *et al.* 2016).

Inefficient control measures of FAW can lead to an estimated average yield loss of 37% (range 21-53%) in maize production throughout Africa (Day *et al.* 2017; Prasanna *et al.* 2018). Under these sets of conditions, FAW has the ability to inflict great damage to maize which may result in yield losses of 8.3 to 20.6 M metric tons per year (with a value of between US\$ 2.48 billion and US\$ 6.19 billion) (Prasanna *et al.* 2018). Day *et al.* (2017) conducted surveys on people's perceptions of the national impact that FAW has in different African countries and respective maize agro-ecological zones. They estimated yield losses of maize in Mozambique and Ghana to be 41.3% (range 23-57%) and 45% (range 22-67%), respectively, with respective mean value of US\$ 146.25 million and US\$ 278.65 million. These data do not emphasize the economic impact on farmers alone but also give an insight to the socio-economic importance of the impact that FAW has on food security of subsistence farming communities as well as seed companies (Day *et al.* 2017; Prasanna *et al.* 2018).

2.9 Integrated pest management

Integrated pest management (IPM) is a strategy that aims to manage pests more effectively by reducing the amount of insecticides used through the integration of biological, physical, cultural and chemical applications as well as genetic modification of crops to make them pest resistant (Boissard *et al.* 2008; Barclay *et al.* 2011; Mazza *et al.* 2014; Christie *et al.* 2015). IPM strategies strive toward long-term solutions in terms of pest management while maintaining a maximum yield for food and economic sustainability as well as environmental health (Way and Van Emden 2000; Tyson 2014). The above-mentioned mechanisms used in IPM are the basic principles required to enhance pest control in an environmental as well as a socio-economically responsible way (Waller 1997; Matteson 2000; Way and Van Emden 2000; Christie *et al.* 2015; Bentivenha *et al.* 2016). This goal to move away from insecticide applications as preferred control option will contribute to more eco-friendly and cost-effective management strategies which will also enhance the quality of crops and the environment, and will contribute to improved human health (Headley 1979; Vincent *et al.* 2003; Boissard *et al.* 2008; Barclay *et al.* 2011; Toleubayev *et al.* 2011; Thorburn 2014; Pretty and Bharucha 2015).

The use of insecticides as part of an IPM strategy should be guided by assessments of pest population numbers present in crop fields (Fig. 2.5) (Hruska and Gladstone 1988; Pinnschmidt *et al.* 1995; Perrin 1997). Decisions in this regards are usually case-specific and depend on a number of factors such as the scale of the farming system, the specific pest species, its biological and physiological characteristics, as well as the crop and its level of pest resistance (Kropff *et al.* 1995).

According to a study conducted by Hruska and Gladstone (1988) in Nicaragua, a minimum infestation level of 40% was required for FAW to result in yield loss of irrigated maize. Decisions to apply insecticides should be supported by economic threshold levels for FAW on maize, taking into account the particular region (or agroecological zone) with its environmental conditions to prevent unwarranted insecticide applications (Fig. 2.5) (Hruska and Gladstone 1988; Liang *et al.* 2012; Petrovskii *et al.* 2014a, b). Once damage to crops have reached the economic threshold level, an intervention has to take place. In the example illustrated in Figure 2.5, insecticides are applied accordingly, to prevent the infestation level from reaching the economic injury level (Hruska and Gladstone 1988; Matteson 2000; Toleubayev *et al.* 2011; Pretty and Bharucha 2015).

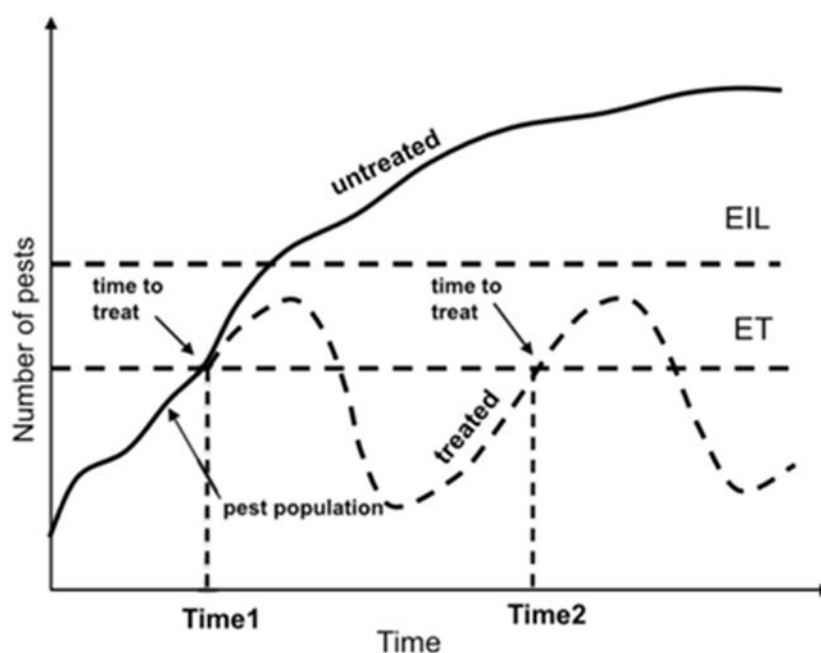


Figure 2.5. The dynamic population change in pest numbers when control insecticide treatments are applied according to the economic threshold (ET) and economic injury level (EIL) of the specific species (Liang *et al.* 2012).

2.10 Economic threshold level

Pedigo (2004) defined the economic threshold level as the amount of crop damage, that if left untreated, will result in economic loss. The economic threshold, which lies just below the economic injury level (Stern *et al.* 1959; Pedigo 2004), can be used as a parameter to indicate the optimal time, in terms of pest population density (Stern *et al.* 1959; Tang *et al.* 2014), to take action by implementing control measures that suppress pest population numbers to prevent economic loss (Pedigo 2004; Larsson 2005; Liang *et al.* 2012; Tang *et al.* 2014).

Regular monitoring is required to determine whether the current pest population numbers will result in economic loss or not. Although maize plants may be tolerant to relatively high levels of foliar damage (Pedigo 2004), environmental conditions influence plant responses to damage thereby changing the tolerance level of the crop (Torres-Vila *et al.* 2003; Rueda *et al.* 2007). An informed decision regarding insecticide application should therefore be made based on information that takes into account various factors such as the economic threshold level, host plant response and prevailing conditions (Pedigo 2004). The economic threshold level varies across different developmental stages, correlating with the susceptibility of the crop and its' respective growth stage (Torres-Vila *et al.* 2003; Larsson 2005). Crops tend to be more resistant to pests as the plant develops toward maturity, therefore raising the economic threshold level (de Freitas Bueno *et al.* 2015). Hruska (2019) indicated that, to be economically profitable, the cost of control of FAW on maize should not exceed US\$ 7.88/ha under general African farming conditions.

2.11 Economic injury level

The economic injury level (EIL) is defined as the minimum number of individuals of a pest population that is required for the shortest period of time which will result in economic loss due to quantitative and qualitative crop damage (Stern *et al.* 1959; Pedigo 2004). According to Larsson (2005), the EIL is reached once the cost of pest suppression to reduce crop damage is equal to the cost of yield loss according to the market value. This can be expressed in terms of an equation, $EIL = C/VIDK$ where the cost of pest control (C), market value of the crop (V), level of damage (D) and the proportion of pest suppression (K) are taken into consideration when determining the EIL and implementing control measures (Pedigo *et al.* 1986; Pedigo 2004). Implementation of IPM and application of insecticides according to an EIL provide an informed way to optimally manage pest population densities, and to prevent redundant misuse of pesticides (Rueda *et al.* 2007).

Quantification of the ET and EIL in practice relates to pest population density within the particular cropping system, and also the level of injury or damage caused by the pests (Pedigo 2004; Prasanna *et al.* 2018). Pest population density often correlates to degree of damage, with the latter which then can be used as a broad-spectrum indicator of pest pressure (Pedigo 2004).

The accuracy of ETLs depend on estimations of possible yield loss based on the degree of damage observed, or the level of infestation, to predict when a pest population density will reach the ETL (Stern *et al.* 1959; Pedigo *et al.* 1986; Pedigo 2004). A high level of knowledge

and research on FAW and how maize plants respond to FAW damage is required to develop ETLs that are applicable to African farming systems (Prasanna *et al.* 2018). To address the lack of ETLs for FAW control in Africa, action thresholds (AT) can be estimated. These ATs should be based on professional judgement and physical evidence gathered by means of scouting, current relevant research on FAW as well as historic data on AT's in region with similar climatic conditions (Prasanna *et al.* 2018).

2.12 Action threshold level

The AT is defined as a time period model that indicates the optimal time at which control measures should be implemented (Pedigo *et al.* 1986; Walker *et al.* 2010). This threshold can be differentiated from the ETL on the basis of its dissociation with the EIL (Pedigo *et al.* 1986). Since the AT is based on similar principles to the ETL, informed decisions can be made regarding insecticide application to achieve optimal pest control (Pedigo *et al.* 1986; Litsinger *et al.* 2006). In addition, the AT focusses on predictable periodic seasonal conditions and fluctuations which commonly result in pest outbreaks (Walker *et al.* 2010). In a study on *Helicoverpa armigera* (Lepidoptera: Noctuidae), Walker *et al.* (2010) reported that the AT can be adjusted according to environmental conditions as well as the biology and physiology of pests to ensure efficient control.

Pesticides are applied according to label instructions, which indicate, among other things, the frequency of spray intervals that are supported by the AT concept, thereby enhancing its applicability in pest management (Hallett and Sears 2012).

Large-scale commercial farming systems aim to maximize their actual yield production in mono-cropping systems despite the high risk of pest outbreaks that can cause serious damage to crops in such systems (Perrin 1997; Oerke and Dehne 2004). Therefore, efficient management and cropping techniques are required which incorporate IPM principles and multiscale pest monitoring systems (Petrovskii *et al.* 2014a, b; Tyson 2014). Commercially available sex pheromone-baited traps have been used in a number of countries for monitoring FAW numbers in maize (Malo *et al.* 2001, 2004) and thus determine ATs.

Pheromone traps can provide early warning of the presence of FAW in an area and contribute to optimization of pest management activities such as initiation of scouting procedures and timely application of insecticides (Cruz *et al.* 2012). Monitoring moth numbers caught with these traps allows farmers to keep track of moth numbers within the cropping system. This may also allow farmers to make informed decisions on whether they need to apply insecticides or not (Cruz *et al.* 2012). The benefit of monitoring infestations by means of pheromone traps

is that plants do not have to be damaged during the scouting process to determine if there are larvae deep inside the whorls of maize plants (Cruz *et al.* 2012).

2.13 Chemical control

Chemical control is the most commonly used and most effective method for FAW control (Lima *et al.* 2010; Christie *et al.* 2015; Tyson 2014). Insecticides which are currently present on the market for FAW are all spray applications. Both spray and granular applications into whorls of maize plants have previously been reported to provide effective control of other lepidopteran maize pests such as maize stem borers (Van Huis 1981; Van den Berg and Nur 1998) which largely occupy the same niche as FAW. These stem borers - mainly *Chilo partellus* (Lepidoptera: Crambidae) and *Busseola fusca* (Lepidoptera: Noctuidae) - have in the past been effectively controlled by several different active ingredients formulated for granular application into plant whorls (Van den Berg and Nur 1998; Silvestri *et al.* 2019).

Resistance evolution is aggravated by the misuse of initially effective insecticides that were not sprayed according to label instructions (Serra and Trumper 2006; Attia *et al.* 2015; Sparks and Nauen 2015). The short life cycle of FAW contributes to its ability to rapidly evolve resistance to commonly used pesticides. Therefore, because the use of insecticides for FAW control in Africa is faced by challenges such as not being economically beneficial for small-scale farmers, non-target effects and resistance evolution, alternative management strategies should be developed (Prasanna *et al.* 2018).

Synthetic insecticides have a high efficiency over a short period of time (Ramkumar *et al.* 2016) although they also have negative environmental impacts. Synthetic compounds are non-specific to their targets and therefore reduce the population numbers of beneficial species as well as negatively affect the health quality of humans and their live-stock (Attia *et al.* 2015; Ramkumar *et al.* 2016; Rodriguez-Saona *et al.* 2016). However, the greatest problem arises with development of resistance against these pesticides (Attia *et al.* 2015; Ramkumar *et al.* 2016).

Insecticides can be classified into different groups based on how they affect the pest by disrupting either their central nervous system, metabolic system or forming crystals that rupture their intestines which leads to starvation or sepsis (Bentivenha *et al.* 2016; IRAC International MoA Working Group 2017). Many different insecticides with different modes of action have been registered for FAW control in South Africa (DAFF 2017).

2.13.1 Neuromuscular insecticides

Organophosphates contain a structure of anticholinestrase which affects the nervous system at the synaptic cleft through the prevention of acetocholeline catabolism (Dewer *et al.* 2016; Abreu-Villaca and Levin 2017). This causes impaired neural impulse transmission to the muscles which leads to death. The organophosphate chlorpyrifos successfully controls a wide range of insect pests (Rodriguez-Saona *et al.* 2016) and is also used for control of FAW. Carbamates were developed with similar function to those of organophosphates and they have a reduced risk factor for humans and animals (Abreu-Villaca and Levin 2017).

Insecticides which are currently on the market for FAW control on maize are all spray applications. Chemical control of maize stem borers, which largely occupy the same niche as FAW in maize, has in the past, before this technology became redundant, also been with granular and dust applications into whorls of plants (Jotwani, 1983; Van den Berg and Van Rensburg, 1993). The stem borers, *C. partellus* and *B. fusca* have in the past been effectively controlled by several different active ingredients formulated for granular application into plant whorls. For example, Van den Berg and Van Rensburg (1993) reported that trichlorfon and beta-cyfluthrin granules provided effective control of stem borers. Jotwani (1983) reported effective use of dust and granular formulations of insecticides for stem borer control in maize and rice.

Carbaryl (Carbaryl® GR, Kombat Stalkborer® granules) and methomyl (Methomyl® EC, Mylomex® 900 SP) have been reported to be effective against the maize earworm *H. armigera* in the mid 1970's; however, extensive application of these carbamates led to resistance evolution (Gunning *et al.* 1992).

Although most of the abovementioned active ingredients have been withdrawn from use in many countries in the world, the granular formulation of pesticides for application into whorls of maize plants may hold promise for FAW control. Compared to spray applications, insecticide granules have longer residual activity due to sustained presence in whorls, and may be more effective in reaching the target pest inside whorls where spray applications do not always reach.

2.13.2 Acetylcholinesterase (AChE) inhibitors

Neonicotinoids and carbamates are classified into the largest class which are the most commonly used insecticides that function through neuromuscular toxins (Simon-Delso *et al.* 2015; Dewer *et al.* 2016). The popularity of insecticides with neuromuscular toxins can be expected due to their fast-acting ability that shows immediate effects. Once the insecticides have entered the insect's body, the sub-units of neonicotinoids or carbamates bind to the

target site in the post synaptic neuron, altering the nAChRs and inhibiting production of acetylcholinesterase enzymes (AChE) within the synaptic cleft, which assist in catabolism of the neurotransmitter acetylcholine (Group 1) (Salgado 1998; Simon-Delso *et al.* 2015; Dewer *et al.* 2016). This disrupts the neural processes of the insect by blocking the site for neural transmission (Simon-Delso *et al.* 2015).

2.13.3 Sodium channel modulators

Type II pyrethroids function as insecticides in a similar way by altering the sodium channels and thus, the flow of sodium ions which produce an action potential that regulates muscular movements (Singh *et al.* 2009; IRAC International MoA Working Group 2017). Beta-cyfluthrin (Bulldock® 0.05 GR) binds to the target site on the voltage-gated sodium channel which prevents the sodium channels from closing (Singh *et al.* 2009; Simon-Delso *et al.* 2015; Dewer *et al.* 2016). In addition, it also reduces the production of acetylcholinesterase and adenosine triphosphatase (total ATPase) (Singh *et al.* 2009). This causes a continuous flow of the sodium ions across the membrane of the axon which initiates hyperexcitation following depolarization leading to paralysis and death (Singh *et al.* 2009; Simon-Delso *et al.* 2015; Dewer *et al.* 2016).

2.13.4 Natural insecticides

Diatomaceous earth (DE) is a natural sedimentary product formed as a result of diatom species that extracted silicon from their aquatic environment that has been fossilised (Round *et al.* 1992; Korunic 1997). Mining and milling of DE reduce the size and moisture content of the particles to a dust like consistency for commercial use (Quarles and Winn 1996; Korunic 1997). The high absorption ability of DE in addition to its non-toxic properties to mammals facilitates the utilization of DE in insecticides (Quarles 1992; Korunic 1997). These small DE particles attach to the rough cuticle surface of larvae that come in direct dermal contact with these insecticides, via sorption and abrasion, which produce pores to the protective wax. This causes an ion leak including body fluids which initiates desiccation that lead to death (Korunic 1997). The DE dust that is applied as an insecticide to the whorl of plants also creates an unfavourable ovipositional surface for pests therefore, minimizing the infestation rate (White *et al.* 1966; Korunic 1997).

Spinosad (Spintor® 0.125% Dust), from part of the naturalyte insecticide group produced by a soil bacterium (*Saccharopolyspora spinosa*) (Pan *et al.* 2011). It is derived from the chemical

components, Spinosyn A and D, which produces the toxic substances present in spinosad (Pan *et al.* 2011).

2.13.5 How insecticides enter the body of an insect

Insecticides kill by entering the body through either direct dermal contact, ingestion of the toxic substance or by means of inhaling toxic fumes that bind to their specific target sites (Vincent *et al.* 2003; Pretty and Bharucha 2015). There exists a great overlap between these methods of entry, with most examples of insecticides uptake including at least two of these entry mechanisms (Boina and Bloomquist 2014). The mechanism of entry correlates with the target site and mode of action of insecticides, with dermal and respiratory uptake largely affecting the nervous system while oral intake impacts the digestive system (Boina and Bloomquist 2014).

The efficiency of insecticide uptake depends on the time of exposure, the toxicity of the insecticide as well as the level of susceptibility of the specific insect (Lee *et al.* 2016). This may vary across or within species among different life stages and sexes due to gender-based functions of certain species (Rodriguez-Saona *et al.* 2016). Environmental conditions also influence the efficiency of soil- and foliar-applied insecticides which could require adjustments of applications in the wet seasons to prevent sufficient dilution of insecticides that contributes to development of resistance.

Foliar-applied insecticides enter the insect body through direct contact or by ingestion when they feed on sprayed leaves (Boina and Bloomquist 2014). It is therefore, important to apply insecticides that are highly effective, to ensure rapid mortality of the target pest after contact or ingestion of the insecticide (Boina and Bloomquist 2014).

2.14 Host plant resistance

Generic host plant resistance is a heritable trait that influences the ability of pests to colonise, reproduce or survive on host plants through antibiosis or antixenosis mechanisms (Headley 1979; Van Emden 1983; Wiseman *et al.* 1994). Leaf feeding resistance to FAW has been reported in maize breeding lines and natural resistance has been reported as a possible tool for control of FAW in Africa (Prasanna *et al.* 2018). Transgenic Bt maize has also been used to effectively to control *S. frugiperda*. Bt maize hybrids that express either Cry1F, Cry1Ab or Cry1A.105 + Cry2Ab2 proteins have been used on a large scale in the USA and Canada (Buntin *et al.* 2004, Siebert *et al.* 2012, Storer *et al.* 2012, Reay-Jones *et al.* 2016) and several

South America countries (Buntin 2008, Storer *et al.* 2012, Farias *et al.* 2014; Bernardi *et al.* 2015).

Since Bt maize produces Cry toxins throughout the growing period, it has been described as an easy and effective way of controlling FAW. The toxins produced in Bt maize leaves are present in plants throughout the growing season and with this technology, no pesticides have to be applied against target pests. Difficulties regarding insecticide applications into plant whorls are therefore addressed through the use of Bt maize. Resistance evolution has already been reported for *S. frugiperda* against Cry1Ac Bt cotton in Puerto Rico USA (Storer *et al.* 2012) and Cry1F Bt maize in Brazil (Farias *et al.* 2014) and in the southern USA (Huang *et al.* 2014). The speed at which resistance evolves emphasizes the unreliability of this technology and indicate the importance of looking into alternative control measures by implantation of integrated pest management.

2.15 Cultural control

Cultural control is defined as any technique that makes the environment unfavourable for the pest species present (Agrios 2005; Van Emden 1983). This technique alters the environmental conditions to become less favourable for the pests (Van Emden 1983). This leads to weakening of the interaction among components of the 'disease triangle' which in turn decreases their efficiency for long-term establishment, colonisation as well as reproduction and survival (Agrios 2005). This may include physical control mechanisms which contribute to an unfavourable environment for the pest species by antixenosis or covering the crops so that they are not able to reach their host plants (Vincent *et al.* 2003). The three main agro-ecological approaches are to improve soil fertility and sustainability, to enhance the strength and stability of the biodiversity, and implementation of optimal managing strategies (Harrison *et al.* 2019). Planning and changing the time of irrigation, for example, forces pests to come out of hiding in the soil and synchronises the period of activity between some pests and their natural enemies (Van Emden 1983). Some of these methods have been known and used for such a long time that they are overlooked as potential methods of pest control. Crop rotation disrupts pest life cycles (Blazy *et al.* 2010; Tyson 2014; Harrison *et al.* 2019) while intercropping may disrupt the host finding and survival of pests (Blazy *et al.* 2010; Tyson 2014).

Bottom-up control is implemented when resistant cultivars are planted which reduces pest survival and damage (Tooker and Frank 2012). This can also be supported by strategies such as intercropping and trap crops that lure pests away from the primary crops (Lee *et al.* 2011;

Tooker and Frank 2012; Harrison *et al.* 2019). Crop rotation can also be implemented to recycle nutrients back into the soil thereby enhancing nutrient uptake and overall fitness of crops, making them less susceptible for FAW and other pest infestations (Tooker and Frank 2012; Harrison *et al.* 2019). Cultural control practices also contribute to enhancing the biodiversity within the cropping system, which promotes the abundance of natural enemies of FAW and other pests (Harrison *et al.* 2019; Kenis *et al.* 2019). However, the success of bottom-up control is dependent on the behavioural preference, of oviposition and nutrient requirements, of the pest species involved (Ouyang *et al.* 2012; Harrison *et al.* 2019). Therefore, the pests should be monitored to determine whether the implemented alterations of conditions have a significant influence on the pest population densities or yield loss (Ouyang *et al.* 2012).

Habitat management to reduce pest population numbers has been reported to be effective for stem borer control in Africa (Khan *et al.* 2000). The “push-pull” system has been developed for stem borer control on maize and sorghum by planting Napier grass, *Pennisetum purpureum*, as a trap crop with *Desmodium* sp. or molasses grass, *Melinis minutiflora*, as an intercrop (Khan *et al.* 2000). These crops are selected based on their effect on the pest’s preference to its host plant where trap crops attract and intercrops repel stem borers (Khan *et al.* 2000). The same “push-pull” system used for controlling stem borers was also reported to provide effective control of FAW on maize in East Africa (Midega *et al.* 2018).

2.16 Biological control

Biocontrol is a highly effective and acceptable method due to its simplicity of using natural predators and parasitoids of the pest to reduce its numbers (Mazza *et al.* 2014; Lacey *et al.* 2015). A wide range of viruses, bacteria, fungi as well as nematodes and other arthropods can also act as biological control agents (Lacey *et al.* 2001; Mazza *et al.* 2014; Lacey *et al.* 2015;). It is preferable that the natural predators or pathogens that are used as biocontrol agents are native to the specific region rather than imported from another region. Therefore, biocontrol agents must be carefully chosen and closely monitored to ensure that they only affect the target pest species with rapid results (Lacey *et al.* 2001; Mazza *et al.* 2014). *Telenomus remus* Nixon (Hymenoptera: Platygasteridae) is one of the most successful biological control agents of lepidopteran pests, including the fall armyworm (Kenis *et al.* 2019). This egg parasitoid parasitizes the entire egg mass as opposed to restricted parasitism provided by *Trichogramma* spp., which only parasitizes the eggs on the periphery of egg batches. The presence of indigenous *T. remus* has been reported in many regions of the

African continent (Kenis *et al.* 2019) thus making it unnecessary to introduce the species from outside the continent.

2.17 People's perceptions of the importance of FAW

A study conducted by Kumela *et al.* (2018) estimated the general knowledge, perceptions and control practices of subsistence farmers in Ethiopia and Kenya, to provide better insight into the contributing risk factors as well as key areas in which knowledge and education on this pest should be improved. The majority of farmers in Ethiopia (93%) and Kenya (97%) have encountered and directly experience the negative effects of FAW infestations and damage to their crops. These farmers were also able to accurately identify and differentiate FAW larvae and their damage symptoms from those of stemborer larvae. According to the survey, Kenya (47.3%) experienced a higher average FAW infestation level than Ethiopia (32%), and these infestations resulted in estimated yield losses of 1381 kg/ha and 934 kg/ha. Control measures varied greatly within and among farmers in these two countries as a result of different cultural practices. Although 48% of these farmers relied on chemical insecticides as a FAW control measure, farmers in Kenya (60%) reported low or no efficacy of these insecticides. Farmers in Ethiopia had largely negative perceptions regarding synthetic pesticides, which according to them had negative impacts on human health and adverse effects on pollinators.

2.18 Structure of thesis

The main objective of this research project was to address the gaps in knowledge regarding the injuriousness of FAW to maize in an African environment. The results generated during this study are reported in different chapters, each addressing a specific topic as follows:

Chapter 3: The effect of different levels of infestation and plant growth stage at infestation on yield loss caused by *Spodoptera frugiperda* in South Africa.

Chapter 4: The effect of protection of maize plants during certain growth stages on yield losses caused by *Spodoptera frugiperda*.

Chapter 5: Efficacy of granular insecticides for control of *Spodoptera frugiperda* in maize whorls.

These chapters are then followed by a brief summary and recommendations (Chapter 6) for future research.

2.19 References

- ABREU-VILLACA, Y. and LEVIN, E.D. 2017. Developmental neurotoxicity of succeeding generations of insecticides. *Environment International* 99: 55-77.
- AGRIOS, G.N. 2005. Plant Pathology. 5th ed. Massachusetts: Academic Press. 383-390 pp.
- AGUIRRE, L.A., HERNANDEZ-JUAREZ, A., FLORES, M., CERNA, E., LANDEROS, J., FRIAS, G.A. and HARRIS, M.K. 2016. Evaluation of foliar damage by *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to genetically modified corn (Poales: Poaceae) in Mexico. *The Florida Entomologist* 99: 276-280.
- ATTIA, S., LEBDI, K.G., HEUSKIN, S., LOGNAY, G. and HANCE, T. 2015. An analysis of potential resistance of the phytophagous mite, *Tetranychus urticae* Koch (Acari: Tetranychidae) to four botanical pesticides. *Biotechnology, Agronomy, Society and Environment Journal* 19: 232-238.
- BALDACCHINO, F., KRCCMAR, S., BERNARD, C., MANON, S. and JAY-ROBERT, P. 2017. The impact of land use and climate on tabanid assemblages in Europe. *Agriculture, Ecosystems and Environment* 239: 112-118.
- BARCLAY, H.J., MATLOCK, R., GILCHRIST, S., SUCKLING, D.M., REYES, J., ENKERLIN, W.R. and VREYSEN, M.J.B. 2011. A conceptual model for assessing the minimum size area for an area-wide integrated pest management program. *International Journal of Agronomy* 1-12. Article ID 409328. [dx.doi.org/10.1155/2011/409328](https://doi.org/10.1155/2011/409328)
- BARDNER, R. and FLETCHER, K.E. 1974. Insect infestations and their effects on the growth and yield of field crops: a review. *Bulletin of Entomological Research* 64: 141-160.
- BENTIVENHA, J.P.F., PAULA-MORAES, S.V., BALDIN, E.L.L., SPECHT, A., DA SILVA, I.F. and HUNT, T.E. 2016. Battle in the New World: *Helicoverpa armigera* versus *Helicoverpa zea* (Lepidoptera: Noctuidae). *PLoS ONE* 11. e0167182. <https://doi.org/10.1371/journal.pone.0167182>.
- BERNARDI, D., SALMERON, E., HORIKOSHI, R.J., BERNARDI, O., DOURADO, P.M., CARVALHO, R.A., MARTINELLI, S., HEAD, G.P. and OMOTO, C. 2015. Cross-resistance between Cry1 proteins in fall armyworm (*Spodoptera frugiperda*) may affect the durability of current pyramided Bt maize hybrids in Brazil. *PLoS ONE* 10: e0140130. <https://doi.org/10.1371/journal.pone.0140130>.

- BLAZY, J-M., TIXIER, P., THOMAS, A., OZIER-LAFONTAINE, H., SALMON, F. and WERY, J. 2010. BANAD: A farm model for ex ante assessment of agro-ecological innovations and its application to banana farms in Guadeloupe. *Agricultural Systems* 103: 221-232.
- BOINA, D.R. and BLOOMQUIST, J.R. 2014. Chemical control of the Asian citrus psyllid and of Huanglongbing disease in citrus. *Pest Management Science* 71: 808-823.
- BOISSARD, P., MARTIN, V. and MOISAN, S. 2008. A cognitive vision approach to early pest detection in greenhouse crops. *Computers and Electronics in Agriculture* 62: 81-93.
- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- BUNTIN, G.D. 2008. Corn expressing Cry1Ab or Cry1F endotoxin for fall armyworm and corn earworm (Lepidoptera: Noctuidae) management in field corn for grain production. *Florida Entomologist* 91: 523-530.
- BUNTIN, G.D., FLANDERS, K.L. and LYNCH, R.E. 2004. Assessment of experimental Bt events against fall armyworm and corn earworm in field corn. *Journal of Economic Entomology* 97: 259-264.
- CHRISTIE, M.E., VAN HOUWELING, E. and ZSELEGCZKY, L. 2015. Mapping gendered pest management knowledge, practices, and pesticide exposure pathways in Ghana and Mali. *Agriculture and Human Values* 32: 761-775.
- CRUZ, I., DE LOURDES CORREA FIGUEIREDO, M., DA SILVA, R.B., DASILVA, I.F., DESOUZA PAULA, C. and FOSTER, J.E. 2012. Using sex pheromone traps in the decisionmaking process for pesticide application against fall armyworm (*Spodoptera frugiperda* [Smith] [Lepidoptera: Noctuidae]) larvae in maize. *International Journal of Pest Management* 58: 83-90. Doi: 10.1080/09670874.2012.655702.
- DAFF. 2017. Department of Agriculture, Forestry and Fisheries (DAFF). Guideline for registered agrochemicals to control Fall armyworm in South Africa. <https://www.daff.gov.za>. Accessed 31 October 2019.
- DAMOS, P. and SOULOPOULOU, P. 2015. Do insect populations die at constant rates as they become older? Contrasting demographic failure kinetics with respect to temperature according to the Weibull Model. *PLOS One*. doi.org/10.1371/journal.pone.0127328
- DAY, R., ABRAHAMS, P., BATEMAN, M., BEALE, T., CLOTTEY, V., COCK, M., COLMENAREZ, Y., CORNIANI, N., EARLY, R., GODWIN, J., GOMEZ, J., MORENO, P.G.,

- MURPHY, S.T., OPPONG-MENSAH, B., PHIRL, N., PRATT, C., SILVESTRI, S. and WITT, A. 2017. Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management* 196-201.
- DE FREITAS BUENO, A., BORTOLOTTI, O.C., POMARI-FERNANDES, A. and DE BARROS FRANCA-NETO, J. 2015. Assessment of a more conservative stinkbug economic threshold for managing stink bugs in Brazilian soybean production. *Crop Protection* 71: 132-137.
- DEWER, Y., POTTIER, M.A., LALOUETTE, L., MARIA, A., DACHER, M., BELZUNCES, L.P., KAIRO, G., RENAULT, D., MAIBECHE, M. and SIAUSSAT, D. 2016. Behavioural and metabolic effects of sublethal doses of two insecticides, chlorpyrifos and methomyl, in the Egyptian cotton leafworm, *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae). *Environmental Science and Pollution Research* 23: 3086-3096.
- DU PLESSIS, H., VAN DEN BERG, J., OTA, N. and KRITICOS, D.J. 2018. *Spodoptera frugiperda*. *CSIROInSTePP Pest Geography* 1-7.
- EARLY, R., GONZALEZ-MORENO, P., MURPHY, S.T. and DAY, R. 2018. Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm. *NeoBiota* 40: 25-50. <https://doi.org/10.3897/neobiota.40.28165>.
- FARIAS, J.R., ANDOW, D.A., HORIKOSHI, R.J., SORGATTO, R.J., FRESIA, P., SANTOS, A.C. and OMOTO, C. 2014. Field-evolved resistance to Cry1F maize by *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Brazil. *Crop Protection* 64: 150-158.
- FENEMORE, P.G. 1982. Plant pests and their control. Wellington, NZ: Butterworths. 271p. ISBN 0-409-60087-3.
- FLANDERS, K.L., BALL, D.M. and COBB, P.P. 2017. Management of FAW in pastures and hay fields. The Alabama Cooperative Extension System (Alabama A&M University and Auburn University). 8 pp.
- GARCIA, A.G., GODOY, W.A., THOMAS, J.M.G., NAGOSHI, R.N. and MEAGHER, R.L. 2018. Delimiting strategic zones for the development of fall armyworm (Lepidoptera: Noctuidae) on corn in the state of Florida. *Journal of Economic Entomology* 111: 120-126.
- GOERGEN, G., KUMAR, P.L., SANKUNG, S.B., TOGOLA, A. and TAMO, M. 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in west and central Africa. *PLoS ONE*. DOI: 10.1371/journal.pone.0165632.

- GUNNING, R.V., BALFE, M.E. and EASTON, C.S. 1992. Carbamate resistance in *Helicoverpa armigera* (Hubner) (Lepidoptera: Noctuidae) in Australia. *Journal of Australian Entomology* 31: 97-103.
- HALLETT, R.H. and SEARS, M.K. 2012. Pheromone-based action thresholds for control of the Swede Midge, *Contarinia nasturtii* (Diptera: Cecidomyiidae), and residual insecticide efficacy in cole crops. *Journal of Economic Entomology* 106: 167-176.
- HARRISON, R.D., THIERFELDER, C., BAUDRON, F., CHINWADA, P., MIDEGA, C., SCHAFFNER, U and VAN DEN BERG, J. 2019. Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management* 243: 318-330.
- HEADLEY, J.C. 1979. Economics of pest control: Have priorities changed? *Farm Chem.* 142: 55-57.
- HERNANDEZ-MENDOZA, J.L., LOPEZ-BARBOSA, E.C., GARZA-GONZALEZ, E. MAYEK-PEREZ, N. 2008. Spatial distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize landraces grown in Colima, Mexico. *International Journal of Tropical Insect Science* 28: 126-129.
- HOGG, D.B., PITRE, H.N. and ANDERSON, R.E. 1982. Assessment of early-season phenology of the fall armyworm (Lepidoptera: Noctuidae) in Mississippi. *Environmental Entomology* 11: 705-710.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CABI Reviews* 14: 1-11.
- HRUSKA, A.J. and GOULD, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology* 90: 611- 622.
- HRUSKA, A.J. and GLADSTONE, S.M. 1988. Effect of period and level of infestation of the fall armyworm, *Spodoptera frugiperda*, on irrigated maize yield. *The Florida Entomologist* 71: 249-254.
- HUANG, F., QURESHI, J.A., MEAGHER JR, R.L., REISIG, D.D., HEAD, G.P., ANDOW, D.A., NI, X., KERNS, D., BUNTIN, G.D., NIU, Y., YANG, F. and DANGAL, V. 2014. Cry1F resistance in fall armyworm *Spodoptera frugiperda*: single gene versus pyramided Bt maize. *PLoS ONE* 9: e112958.

- IRAC. Insecticide Resistance Action Committee. For additional information on insect resistance, modes of action and monitoring visit the Insecticide Resistance Action Committee (IRAC) on the web at <http://www.iraconline.org/>
- JACOBS, A., VAN VUUREN, A. and RONG, I.H. 2018. Characterisation of the fall armyworm (*Spodoptera frugiperda* J.E. Smith) (Lepidoptera: Noctuidae) from South Africa. *African Entomology* 26: 45-49.
- JAMJANYA, T. 1987. Consumption, utilization, biology, and economic injury level of fall armyworm, *Spodoptera frugiperda* (J.E. Smith), on selected Bermudagrasses. LSU Historical Dissertations and Theses. 4362. https://digitalcommons.lsu.edu/gradschool_disstheses/4362.
- JOTWANI. 1983. Chemical control of cereal stemborers. *Insect Science and its Application* 4: 185-189.
- KENIS, M., DU PLESSIS, H., VAN DEN BERG, J., BA, M.N., GOERGEN, G., KWADJO, K.E., BAOUA, I., TEFERA, T., BUDDIE, A., CAFA, G., OFFORD, L., RWOMUSHANA, I. and POLASZEK, A. 2019. *Telenomus remus*, a candidate parasitoid for the biological control of *Spodoptera frugiperda* in Africa, is already present on the continent. *Insects* 10: 1-10. doi:10.3390/insects10040092.
- KHAN, Z.R., PICKETT, J.A, VAN DEN BERG, J., WADHAMS, L.J. and WOODCOCK, C.M. 2000. Exploiting chemical ecology and species diversity: stem borer and striga control for maize and sorghum in Africa. *Pest Management Science* 56: 957-962.
- KORUNIC, Z. 1997. Diatomaceous earth, a group of natural insecticides. *Journal of Stored Products Research* 34: 87-97.
- KROPFF, M.J., TENG, P.S. and RABBINGE, R. 1995. The challenge of linking pest and crop models. *Agricultural Systems* 49: 413-434.
- KUMELA, T., SIMIYU, J., SISAY, B., LIKHAYO, P., MENDESIL, E., GOHOLE, L. and TEFERA, T. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management* 1-9.
- LABORDA, R., GALAN-BLESAA, J., SANCHEZ-DOMINGOA, A., XAMANI, P., ESTRUCH, V.D., SELFA, J., GUERRIERI, E. and RODRIGO, E. 2015. Preliminary study on the biology, natural enemies and chemical control of the invasive *Macrohormotoma gladiata*

- (Kuwayama) on urban *Ficus microcarpa* L. trees in Valencia (SE Spain). *Urban Forestry and Urban Greening* 14: 123-128.
- LACEY, L.A., FRUTOS, R., KAYA, H.K. and VAIL, P. 2001. Insect pathogens as biological control agents: Do they have a future? *Biological Control* 21: 230-248.
- LACEY, L.A., GRZYWACZ, D., SHAPIRO-ILAN, D.I., FRUTOS, R., BROWNBRIDGE, M. and GOETTEL, M.S. 2015. Insect pathogen as biological control agent: Back to the future. *Journal of Invertebrate Pathology* 132: 1-41.
- LARSSON, H. 2005. A crop model and economic thresholds for the grain aphid, *Sitobion avenae* (F.), in winter wheat in southern Sweden. *Crop Protection* 24: 397-405.
- LEE, D.H., NYROP, J.P. and SANDERSON, J.P. 2011. Avoidance of natural enemies by adult whiteflies, *Bemisia argentifolii*, and effects on host plant choice. *Biological Control* 58: 302-309.
- LEE, M., LIU, Z., HUANG, R. and TONG, W. 2016. Application of dynamic topic models to toxicogenomics data. *BMC Bioinformatics* 17: 154-186.
- LIANG, J., TANG, S. and CHEKE, R.A. 2012. An integrated pest management model with delayed responses to pesticide applications and its threshold dynamics. *Nonlinear Analysis: Real World Applications* 13: 2352-2374.
- LIMA, M.S., SILVA, P.S.L., OLIVEIRA, O.F., SILVA, K.M.B. and FREITAS, F.C.L. 2010. Corn yield response to weed and fall armyworm controls. *Planta Daninha, Viscosa-MG* 28: 103-111.
- LINDUSKA, J.J and HARRISON, F.P. 1986. Adult sampling as a means of predicting damage levels of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 69: 487-491.
- LITSINGER, J.A., BANDONG, J.P., CANAPI, B.L., DELA-CRUZ, C.G., PANTUA, P.C., ALVIOLA, A.L. and BATAY-AN, III E.H. 2006. Evaluation of action thresholds for chronic rice insect pests in the Philippines. III. Leafrollers. *International Journal of Pest Management* 52: 181-194.
- LUGINBILL, P. 1928. The Fall Armyworm. *USDA Technical Bulletin* 34: 91.
- MALO, E.A., CRUZ-LÓPEZ, L., VALLE-MORA, J.L., VIRGEN, A., SÁNCHEZ, J. A. and ROJAS, C.J. 2001. Evaluation of commercial pheromone lures and traps for monitoring

- male fall armyworm (Lepidoptera: Noctuidae) in the coastal region of Chiapas, Mexico. *Florida Entomologist* 84: 659–664.
- MALO, E.A., BAHENA, F., MIRANDA, M.A. and VALLE-MORA, J. 2004. Factors affecting the trapping of males of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) with pheromones in Mexico. *Florida Entomologist* 87: 88-293.
- MATTESON, P.C. 2000. Insect pest management in tropical Asian irrigated rice. *Annual Review of Entomology* 45: 549-574.
- MAZZA, G., FRANCARDI, V., SIMONI, S., BENVENUTI, C., CERVO, R., FALEIRO, J.R., LLACER, E., LONGO, S., NANNELLI, R., TARASCO, E. and ROVERSI, P.F. 2014. An overview on the natural enemies of *Rhynchophorus* palm weevils, with focus on *R. ferrugineus*. *Biological Control* 77: 83-92.
- MIDEGA, C.A.O., PITCHAR, J.O., PICKETT, J.A., HAILU, G.W. and KHAN, Z.R. 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J.E. Smith), in maize in East Africa. *Crop Protection* 105: 10-15.
- MONTEZANO, D.G., SPECHT, A., SOSA-GÓMEZ, D.R., ROQUE-SPECHT, V.F., SOUSA-SILVA, J.C., PAULA-MORAES, S.V., PETERSON, J.A. and HUNT, T.E. 2018. Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. *African Entomology* 26: 286–300.
- MORRILL, W.L. and GREENE, G.L. 1973. Distribution of fall armyworm larvae. 2. Influence of biology and behaviour of larvae on selection of feeding sites. *Environmental Entomology* 2: 415-418.
- MORRILL, W.L. and GREENE, G.L. 1974. Survival of fall armyworm larvae and yields of field corn after artificial infestations. *Journal of Economic Entomology* 67: 119-123.
- OERKE, E.C. and DEHNE, H.W. 2004. Safeguarding production – losses in major crops and the role of crop protection. *Crop Protection* 23: 275-285.
- OUYANG, F., MEN, X., YANG, B., SU, J., ZHANG, Y., ZHAO, Z. and GE, F. 2012. Maize benefits the predatory beetle, *Propylea japonica* (Thunberg), to provide potential to enhance biological control for aphids in cotton. *PLoS ONE* 7: 1-16.
- PAN, Y., YANG, X., LI, ZHANG, R., HU, Y., ZHOU, Y., WANG, J. and ZHU, B. 2011. Genome sequence of the Spinosyns-producing bacterium *Saccharopolyspora spinosa* NRRL 18395. *Journal of Bacteriology* 193: 3150-3151.

- PEDIGO, L.P. 2004. Economic thresholds and economic injury levels. National IPM Network. <http://ipmworld.umn.edu/chapters/pedigo.htm>
- PEDIGO, L.P., HUTCHINS, S.H. and HIGLEY, L.G. 1986. Economic injury levels in theory and practice. *Annual Review of Entomology* 31: 341-368.
- PERRIN, R.M. 1997. Crop protection: taking stock for the new millennium. *Crop Protection* 16: 449-456.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014a. Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks. *Physics of life reviews* 11: 467-525.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014b. Multiscale ecology of agroecosystems is an emerging research field that can provide a stronger theoretical background for the integrated pest management. Reply to comments on "Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks". *Physics of life reviews* 11: 536-539.
- PINNSCHMIDT, H.O., BATCHELOR, W.D. and TENG, P.S. 1995. Simulation of multiple species pest damage in rice using CERES-rice. *Agricultural Systems* 48: 193-222.
- PRASANNA, B.M., HUESING, J.E., EDDY, R. and PESCHKE, V.M. (eds). 2018. Fall armyworm in Africa: A guide for integrated pest management, First Edition. Mexico, CDMX: CIMMYT.
- PRETTY, J. and BHARUCHA, Z.P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* 6: 152-182.
- QUARLES, W. 1992. Diatomaceous earth for pest control. *IPM Practitioner* 14: 1-11.
- QUARLES, W. and WINN, P. 1996. Diatomaceous earth and stored product pests. *IPM Practitioner* 18: 1-10.
- RAMKUMAR, G., KARTHI, S., MUTHUSAMY, R., SUGANYA, P., NATARAJAN, D., KWEKA, E.J. and SHIVAKUMAR, M.S. 2016. Mosquitocidal effect of *Glycosmis pentaphylla* leaf extracts against three mosquito species (Diptera: Culicidae). *PLoS ONE* 11: 1-11.
- REAY-JONES, F.P.F., BESSIN, R.T., BREWER, M.J., BUNTIN, D.G., CATCHOT, A.L., COOK, D.R., FLANDERS, K.L., KERNS, D.L., PORTER, R.P., REISIG, D.D., STEWART, S.D. and RICE, M.E. 2016. Impact of Lepidoptera (Crambidae, Noctuidae, and Pyralidae)

- pests on corn containing pyramided Bt traits and a blended refuge in the southern United States. *Journal of Economic Entomology* 109: 1859-1871.
- RODRIGUEZ-SAONA, C., WANUMEN, A.C., SALAMANCA, J., HOLDCRAFT, R. and KYRYCZENKO-ROTH, V. 2016. Toxicity of insecticides on various life stages of two Tortricid pests of cranberries and on a non-target predator. *Insects* 7: 1-20.
- ROSE, A.H., SILVERSIDES, R.H. and LINDQUIST, O.H. 1975. Migration flight by an aphid, *Rhopalosiphum maidis* (Hemiptera: Aphididae) and a noctuid, *Spodoptera frugiperda* (Lep.: Noctuidae). *The Canadian Entomologist* 107: 567-576.
- ROSSING, W.A.H. and HEONG, K.L. 1997. Opportunities for using systems approaches in pest management. *Field Crops Research* 51: 83-100.
- ROUND, F. E., CRAWFORD, R. M. and MANN, D. G. 1992. The Diatoms. Biology and Morphology of the genera. *Cambridge University Press*, New York, USA.
- RUEDA, A., BADENES-PEREZ, F.R. and SHELTON, A.M. 2007. Developing economic thresholds for onion thrips in Honduras. *Crop Protection* 26: 1099-1107.
- SADEK, M.M. 2011. Complementary behaviour of maternal and offspring *Spodoptera littoralis*: Oviposition site selection and larval movement together maximize performance. *Journal of Insect Behaviour* 24: 67-82.
- SALGADO, V.L. 1998. Studies on the mode of action of spinosad: insect symptoms and physiological correlates. *Pesticide Biochemistry and Physiology* 60: 91-102.
- SERRA, G.V. and TRUMPER, E.V. 2006. Sequential sampling protocols for *Spodoptera frugiperda* (Lepidoptera: Noctuidae), on *Zea mays* fields: influence of sampling unit size. *Bulletin of Entomological Research* 96: 471-477.
- SIEBERT, M.W., NOLTING, S.P., HENDRIX, W., DHAVALA, S., CRAIG, C., LEONARD, B.R., STEWART, S.D. ALL, J., MUSSER, F.R., BUNTIN, G.D and SAMUEL, L. 2012. Evaluation of corn hybrids expressing Cry1F, Cry1A.105, Cry2Ab2, Cry34Ab1/Cry35Ab1, and Cry3Bb1 against Southern United States insect pests. *Journal of Economic Entomology* 105: 1825-1834.
- SILVESTRI, S., MACHARIA, M. and UZAYISENGA, B. 2019. Analysing the potential of plant clinics to boost crop protection in Rwanda through adoption of IPM: the case of maize and maize stem borers. *Food Security* 11: 301-315.

- SIMON-DELISO, N., AMARAL-ROGGERS, V., BELZUNCES, L.P., BONMATIN, J.M., CHAGNON, M., DOWNS, C., FURLAN, L., GIBBONS, D.W., GIORIO, C., GIROLAMI, V., GOULSON, D., KREUTZWEISER, D.P., KRUPKE, C.H., LIESS, M., LONG, E., MCFIELD, M., MINEAU, P., MITCHELL, E.A.D., MORRISSEY, C.A., NOOME, D.A., PISA, L., SETTELE, J., STARK, J.D., TAPPARO, A., VAN DYCK, H., VAN PRAAGH, J., VAN DER SLUIJS, J.P., WHITEHORN, P.R. and WIEMERS, M. 2015. Systemic insecticides (neonicotinoids and fipronil): trends, uses, mode of action and metabolites. *Environmental Science and Pollution Research* 22: 5-34.
- SINGH, A.K., SAXENA, P.N. and SHARMA, H.N. 2009. Stress induced by beta-cyfluthrin, a type-2 pyrethroid, on brain biochemistry of albino rat (*Rattus novogicus*). *Biology and Medicine* 1: 74-86.
- SOPER, A.M., WHITWORTH, R.J. and MC CORNACK, B.P. 2018. Sorghum seed maturity affects the weight and feeding duration of immature corn earworm, *Helicoverpa zea*, and fall armyworm, *Spodoptera frugiperda*, in the laboratory. *Journal of Insect Science* 13: 1-15.
- SPARKS, T.C. and NAUEN, R. 2015. IRAC: Mode of action classification and insecticide resistance management. *Pesticide Biochemistry and Physiology* 121: 122-128.
- STAPEL, J.O., WATERS, D.J., RUBBERSON, J.J. and LEWIS, W.J. 1998. Development and behaviour of *Spodoptera exigua* (Lepidoptera: Noctuidae) larvae in choice tests with food substrates containing toxins of *Bacillus thuringiensis*. *Biological Control* 11: 29-37.
- STERN, V. M. 1973. Economic thresholds. *Annual Review of Entomology* 18: 259-80.
- STERN, V.M., SMITH, R.F., VAN DEN BOSCH, R. and HAGEN, K.S. 1959. The integrated control concept. *Hilgardia* 29: 81-101.
- STORER, N.P., KUBISZAK, M.E., KINGJ.E., THOMPSON, G.D., and SANTOS, A.C. 2012. Status of resistance to Bt maize in *Spodoptera frugiperda*: lessons from Puerto Rico. *Journal of Invertebrate Pathology* 110: 294-300.
- TANG, G., QIN, W. and TANG, S. 2014. Complex dynamics and switching transients in periodically forced Filippov prey-predator system. *Chaos, Solitons and Fractals* 61: 13-23.
- THORBURN, C. 2014. Empire strikes back: The making and unmaking of Indonesia's national integrated pest management program. *Agroecology and Sustainable Food Systems* 38: 3-24.

- TOLEUBAYEV, K., JANSEN, K. and VAN HUIS, A. 2011. From integrated pest management to indiscriminate pesticide use in Kazakhstan. *Journal of Sustainable Agriculture* 35: 350-375.
- TOOKER, J.F. and FRANK, S.D. 2012. Genotypically diverse cultivar mixtures for insect pest management and increased crop yields. *Journal of Applied Ecology* 49: 974–985.
- TORRES-VILA, L.M., RODRIGUEZ-MOLINA, M.C. and LACASA-PLASENCIA, A. 2003. Impact of *Helicoverpa armigera* larval density and crop phenology on yield and quality losses in processing tomato: developing fruit count-based damage thresholds for IPM decision-making. *Crop Protection* 22: 521-532.
- TYSON, R.C. 2014. Pest control: A modelling approach. Comment on “Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks” by S. Petrovskii, N. Petrovskaya and D. Bearup. *Physics of Life Reviews* 11: 526-528.
- VAN DEN BERG, J. and NUR, A.F. Chemical control. In *Cereal Stem Borers in Africa: Economic Importance, Taxonomy, Natural Enemies and Control*; Polaszek, A., Ed.; CABI: Wallingford, UK, 1998; ISBN 085-199-175-0.
- VAN DEN BERG, J. and VAN RENSBURG, J.B.J., 1993. Importance, of persistence and synergistic effects in the chemical control of *Chilo partellus*. *Applied Plant Science* 7: 5-7.
- VAN EMDEN, H.F. 1983. The anatomy of a pest management program. In: Statistical and mathematical methods in population dynamics and pest control. (Cavalloro, R. Ed.). Proceedings of a meeting of EC Experts’ meeting / Parma, 26 – 28 October 1983.
- VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.
- VINCENT, C., HALLMAN, G., PANNETON, B. and FLEURAT-LESSARD, F. 2003. Management of agricultural insects with physical control methods. *Annual Review of Entomology* 48: 261-81.
- WALKER, G.P., HERMAN, T.J.B., KALE, A.J. and WALLACE, A.R. 2010. An adjustable action threshold using larval parasitism of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in IPM for processing tomatoes. *Biological Control* 52: 30-36.
- WALLER, P.J. 1997. Sustainable helminth control of ruminants in developing countries. *Veterinary Parasitology* 71: 195-207.

WAY, M.J. and VAN EMDEN, H.F. 2000. Integrated pest management in practice - pathways towards successful application. *Crop Protection* 19: 81-103.

WHITE, G.D., BERNDT, W.L. and WILSON, J.L. 1975. Evaluating diatomaceous earth, silica aerogel dusts, and malathion to protect stored wheat from insects USDA/ARS. *Marketing Research Report* 1038: 18.

WISEMAN, B.R. 1994. Plant resistance to insects in integrated pest management. *Plant Disease* 78: 927-932.

Chapter 3

The effect of different levels of infestation and plant growth stage at infestation on yield loss caused by *Spodoptera frugiperda* in South Africa

Abstract

Damage by larvae of the Fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), results in significant yield losses of maize in sub-Saharan Africa. However, the lack of data on infestation levels and yield loss caused by FAW in African environments complicates general management decisions and, more specifically, decisions regarding applications of insecticides. Poor correlations between the severity of leaf damage, infestation level (incidence of damaged plants) and yield loss have previously been reported from South America where this pest is indigenous. This study was conducted to determine the relationship between severity of maize leaf damage, incidence of damaged plants (%) and yield responses of plants. Three field trials were conducted of which one was under natural infestation. In the other two trials, plants were artificially inoculated with FAW larvae at different infestation levels per plot (% infested plants) and at different growth stages. Each trial was set up as a split-plot design of which one block was not treated and the other sprayed with an insecticide to allow for quantification of the yield response of plants that were not sprayed. Results showed contradicting correlations ($r = 0.017$ and $r = 0.70$) between severity of leaf damage and yield between trials. There was a negative correlation between the incidence (%) of infested plants and yield per plot. There were no differences in yield per plot when plants were inoculated with FAW larvae at different plant growth stages. The largest yield gains due to repeated insecticide applications were in plots where the percentage of infested plants was between 30 and 60%. The economics of these applications were, however, not determined.

Key words: Economic threshold level; leaf damage; plant injury

3.1 Introduction

Spodoptera frugiperda (FAW) has become a very serious pest of maize in Africa since it was first detected on the continent in 2016 (Goergen *et al.* 2016; Prasanna *et al.* 2018; Sisay *et al.* 2019). Yield losses in the year following the detection of FAW in sub-Saharan Africa were estimated to be very high. For example, Day *et al.* (2017) and Prasanna *et al.* (2018) estimated that poor control measures against FAW could lead to an average yield loss of 37% (range 21-53%). It was estimated that, under African farming conditions, FAW had the ability to inflict yield losses of 8.3 to 20.6 M metric tons per year (valued at between US\$ 2.48 billion and US\$ 6.19 billion) (Abrahams *et al.* 2017; Prasanna *et al.* 2018). Surveys conducted by Day *et al.* (2017), based on people's perceptions, estimated losses of maize due to FAW in Mozambique and Ghana at 41.3% (range 23-57%) and 45% (range 22-67%), respectively.

The relationship between leaf damage caused by FAW larvae and subsequent plant response to damage is not clear and hampers decision making regarding whether or when to initiate control actions such as the application of insecticides. The degree of yield loss caused by FAW depends largely on the frequency and severity of damage, and the plant growth stage during which larvae feed on plants (Fenimore 1982; Gross *et al.* 1982; Harrison 1984; Buntin 1986; Ortega 1987). Buntin (1986) reported a strong correlation between plant growth stage at the time that damage is inflicted and yield loss. Actual yield losses vary widely and there seems to be a poor correlation between infestation level (% infested plants) and yield loss. For example, yield loss of 45% (Hruska and Gladstone 1988) and 18% (Cruz and Turpin 1983) were recorded in Nicaragua and southern Louisiana, respectively in maize fields that were both 100% infested with FAW larvae. Yield losses due to FAW in maize have been reported to be between 30 and 70% in Latin America (Van Huis 1981; Hruska and Gould 1997; Lima *et al.* 2010; Aguirre *et al.* 2016). According to a study conducted by Hruska and Gladstone (1988) in Nicaragua, a minimum infestation level of 40% was required for FAW to result in yield loss of irrigated maize.

In Africa, however, recent reports of yield losses as a result of FAW damage in maize production systems seem to be much lower. It was reported that maize plants can tolerate up to 70% defoliation without causing significant yield losses (Baudron *et al.* 2019; Hruska 2019). Baudron *et al.* (2019) reported that the FAW infestation levels on small holder farmers' fields in Zimbabwe ranged between 32 and 48%, and estimated yield loss to be 11.6%, which is lower than that reported in many other studies conducted in the Americas. Kumela *et al.* (2018) estimated yield losses of 1381 kg/ha and 934 kg/ha in Kenya and Ethiopia, respectively, and reported that 48% of farmers relied on chemical insecticides as a control measure. In Cameroon, Kuate *et al.* (2019) also reported common use of pesticides to control FAW.

Although FAW feeds on maize plants of all growth stages, moths tend to show an ovipositional preference for plants in younger vegetative stages (Harrison 1984; Ortega 1987; Hardke *et al.* 2011). This usually results in high levels of FAW infestation on young plants (Kuate *et al.* 2019), which may lead to complete defoliation (Harrison 1984; Buntin 1986). However, yield losses suffered by maize plants are mostly influenced by the specific part of the plant that is damaged (growth point, leaves, tassel, silk and ears) (Buntin 1986). Brown and Mohamed (1972) reported that as long as the growth point (apical meristem) remains intact, maize plants are highly tolerant to extensive foliar damage, especially during the younger vegetative stages. Foliar damage which is most visible and threatening to farmers can more easily be compensated for by maize plants (Buntin 1986). This high level of tolerance expressed by younger maize plants during the early- to mid-whorl stages (Brown and Mohamed 1972; Harrison 1984), is ascribed to the longer recovery period that is available before tassel formation and ear development (Buntin 1986; Nelissen *et al.* 2012). Maize plants have an extensive foliar canopy and are able to tolerate high levels of defoliation before any measurable losses occur (Brown and Mohamed 1972; Buntin 1986).

Decisions to apply insecticides should be supported by economic threshold levels, taking into account important aspects that may influence the response of maize plants to pest damage, for example, the agroecological zone with its specific environmental conditions, expected yield and time and level of pest attack, to prevent unwarranted insecticide applications (Liang *et al.* 2012; Petrovskii *et al.* 2014a, b; Hruska 2019). Unnecessary insecticide applications do not only have economic implications but also have adverse effects on beneficial organisms that play a role in suppressing FAW numbers inside maize fields (Harrison *et al.* 2019).

Knowledge regarding the relationship between foliar damage caused by FAW larval feeding and yield loss will contribute to improved decision making regarding the use of insecticides and development of action thresholds which will improve the efficacy and economics of control and protect beneficial organism (Buntin 1986; Hruska and Gould 1997; Harrison *et al.* 2019; Hruska 2019).

The aims of this study were to: 1) determine the effect of different levels of FAW infestation on maize yield loss, 2) determine the effect of FAW damage during certain plant growth stages on yield loss, and 3) to determine the effect of different levels of severity of foliar damage inflicted by FAW on yield loss.

3.2 Materials and methods

3.2.1 General description of trial site

Three field trials were conducted during the 2017/18 and 2018/19 growing seasons. Field trials 1 and 2 were conducted at the experiment farm of the ARC-Grain Crops in Potchefstroom, South Africa. Due to the absence of natural FAW infestation during the experimental period at the ARC experimental farm, the different treatments could easily be manipulated by means of artificial inoculation with FAW larvae. Field trial 3 was conducted at an experiment farm in Malelane, South Africa. The sub-tropical climate at the Malelane site allowed for FAW populations to persist throughout the year and high natural infestation levels occurred. A herbicide-tolerant maize hybrid was planted in all trials to facilitate easy weed control.

3.2.2 Rearing of *Spodoptera frugiperda*

Spodoptera frugiperda larvae were collected from whorls of infested maize plants in a maize field in the Groblersdal area in Limpopo Province (25°04'54.8"S, 29°23'56.5"E) in January 2019. These field-collected larvae were reared in plastic containers (38 cm in length, 27 cm in width and 14.5 cm in height) covered with mesh lids to allow sufficient air flow within the cages. Larvae were reared on an ARC-artificial diet until pupation. Pupae were collected from the rearing containers and placed into oviposition cages. Each cage also contained a piece of creased wax paper as an ovipositional surface. A piece of cotton wool soaked in a 10% sugar solution was provided as a food source for moths. Moths were transferred to new cages with freshly prepared sugar solution and wax paper every third day to prevent microbial contamination and to ensure optimal fitness.

Egg batches were collected each day from the respective moth cages and placed in zip-lock bags until the larvae hatched. Larvae were reared on the ARC-artificial diet described in Prasanna *et al.* (2018). Larval rearing was conducted in a climate-controlled room set at 26 ± 1 °C, 70 ± 5% RH and a 14:10 L:D photoperiod.

A total of 300 petri dishes were filled with diet and five neonate larvae were placed onto the diet inside each petri dish by means of a small paint brush. Larvae were reared on this diet for seven days, until they reached the 3rd instar, after which they were removed from the diet and placed in small plastic containers (30 ml) for transport to fields where plants were inoculated.

3.2.3 Field Trial 1: The relationship between infestation level (% incidence) of damaged plants) and yield

The aim of this trial was to determine the relationship between incidence of infested plants, yield, and yield loss. This field trial was planted in mid-November 2018. The experimental field consisted of 8 rows, 100 m in length at a 1.5 m inter-row spacing.

The five treatments in each block were five different levels of infestation (percentage inoculated plants per plot): 0, 10, 20, 40 and 100% inoculated plants per plot row. Each treatment was replicated four times and each replicate consisted of a row of 20 plants.

The designated plants in each plot were inoculated with three 3rd-instar larvae each during the V6/7 growth stage (Fig. 3.1). Inoculated plants were clearly marked with a tag attached to the plant. Larval feeding damage was rated according to the Davis scale (1-9 damage rating) (Table 3.1; Fig. 3.2) (Davis *et al.* 1992) seven days after inoculation. The severity of damage symptoms was rated 14 days after FAW inoculation (V9 stage) for all plants, both inoculated and not inoculated, to account for possible damage caused by larvae that migrated to uninoculated plants. Leaf damage score was indicated on a label tied to the stem of each plant.



Figure 3.1. Inoculation of plants with 3rd-instar larvae in trial 1.

Table 3.2. Description of the degrees of severity of damage caused by larvae of *Spodoptera frugiperda* to maize leaves according to the Davis 1-9 rating scale (Davis *et al.* 1992).

Score	Damage description on whorl leaves
1	No leaf damage
2	Exclusively pinholes
3	Pinholes and a few enlarged lesions (1.3 cm), without complete penetration through all the leaf tissues (holes).
4	Several small and few enlarged lesions (with complete penetration through all the leaf-tissue layers) that are 1.3 cm to 2.5 cm in length.
5	Several enlarged lesions that vary in size and shape. Few small circular lesions with most greater than 2.5 cm in length.
6	Many irregular-shaped enlarged lesions and holes that vary in size on many of the whorl and furl leaves.
7	Many irregular-shaped enlarged lesions that vary in size in addition to enlarged holes on most of the whorl and furl leaves
8	Many irregular-shaped enlarged lesions that vary in size in addition to many enlarged holes on most of the whorl and furl leaves.
9	Complete destruction of the whorl and furl leaves, which may sometimes include the growing points of maize plants.

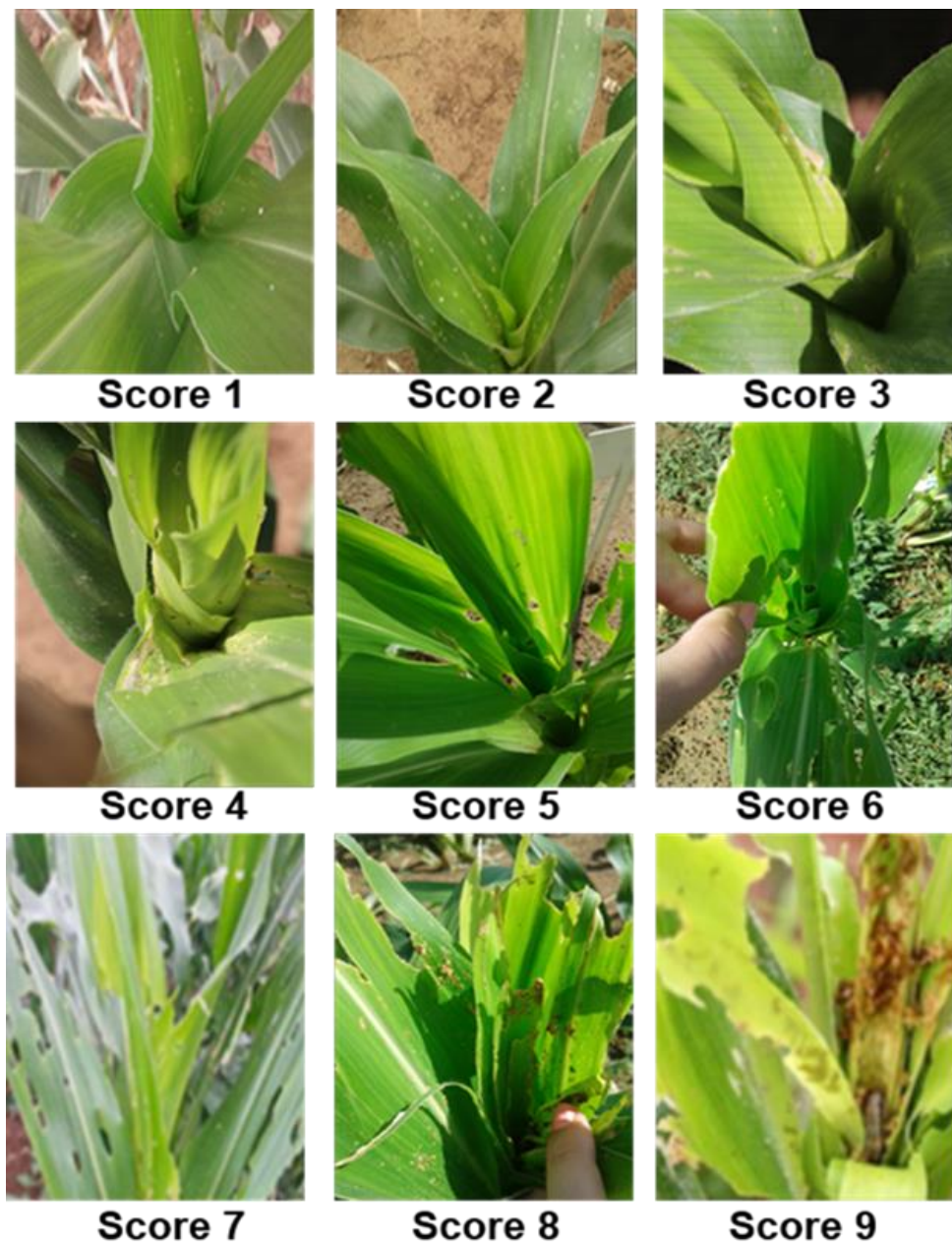


Figure 3.3. Levels of foliar damage based on the 1-9 scale developed by Davis *et al.* (1992). The Davis damage rating scale represents the level of feeding by larvae on furl and whorl leaves of plants (Davis *et al.* 1992). These values can be used as proxy for larval size and larval development over time which indicate the level of resistance of the maize variety to FAW larval feeding (Davis *et al.* 1992).

One of the plots was sprayed with Methomyl® SP 7 days after inoculation to prevent further damage to plants. The other plot was left unsprayed. Yield from plants in the sprayed plot served as the basis for calculating % yield loss in the unsprayed plot.

Ears were harvested and bagged per plant once the crops had dried and the kernels tested below 14% moisture levels. Ears were hand-threshed. Moisture analysis was conducted on

the maize kernels of each plot and used to compensate for the differences in moisture content of kernels between plants. Grain mass was calculated at a moisture content of 11%. Yield loss was calculated and expressed as a percentage in terms of yield of uninfested plants.

3.2.4 Trial 2: The effect of plant growth stage and time of inoculation on yield loss

The aim of this trial was to determine the effect of FAW infestation at different plant growth stages on damage and yield loss. Two blocks were planted and used as a split-plot design with five treatments (Table 3.2). Plants in one of the blocks were sprayed with the insecticide methomyl (Methomyl® SP), seven days after FAW inoculation was done, to kill larvae and prevent further damage to plants. The planting date was mid-January 2019.

Table 3.2. Description of treatments, showing plant growth stage at the time of inoculation with *Spodoptera frugiperda* larvae and insecticide application. V = vegetative stage, Boot stage.

Treatments	
sub-plot 1: Unsprayed Growth stage (weeks after seedling emergence, WAE)	sub-plot 2: Sprayed Plant age at time of insecticide application
No inoculation (Control)	No inoculation (Control)
V4 stage (3 WAE)	4 WAE
V7 stage (5 WAE)	6 WAE
V10 stage (7 WAE)	8 WAE
Boot stage (9 WAE)	10 WAE

Each treatment was replicated four times and each replicate consisted of a row of 20 plants. All plants in both blocks were inoculated with three 3rd-instar larvae per plant when plants were in the respective growth stages. Larvae were placed into plant whorls. With the inoculation at the pre-tassel stage, larvae were placed next to the tassel rolls that started to appear.

Although plants were inoculated at different growth stages, the insecticide applications were done 7 days after inoculation. The larvae were assumed to be in the 5th or 6th instar at that time, since it was 7 days after 3rd instar (7-day old) larvae were inoculated into plants. The application of an insecticide to kill the larvae after a 7-day period, therefore implies that plants

were not only inoculated at different growth stages, but also that plants were protected against damage during certain window-periods. The data therefore represent plant reaction to larval feeding damage over a 7-day period during, for example, the V4-stage and tassel stage.

Larval foliar feeding damage was rated according to the Davis scale for each plant in both blocks. Damage symptoms were rated at seven days after inoculation. The rating of damage for plants that were inoculated during the pre-tassel stage was done by scoring the severity on the upper most leaves below the emerged tassel. Leaf damage rating was indicated on a label tied to the stem of each plant. A mean damage rating was calculated for each plot.

Maize ears of all the plants in each plot were harvested and placed in bags. Ears were threshed and moisture content determined as described previously. Yield loss of plants in the unsprayed plot was expressed as a percentage of the yield of plants in sprayed plots.

3.2.5 Trial 3: The effect of different levels of FAW infestation and insecticide application on yield

The aim with this trial was to assess the levels of yield loss associated with different levels of natural FAW infestation (incidence of plants per plot exhibiting larval feeding damage symptoms) and to determine the effect of full protection from FAW by multiple insecticide applications on yield gain. This trial was planted at an experiment farm in Malelane, South Africa during early-February 2019. Insecticides were applied twice within the week just after seedling emergence, before the trial commenced. This was done as a routine measure to provide very early protection to ensure the successful establishment of the trial.

The block of maize, consisting of 12 rows of 150 m in length, was planted using an inter-row spacing of 1.0 m. Two rows on each side of the block served as guard rows and the eight central rows were used for the experiment. Each plot consisted of two adjacent 5-m long rows. Plots were separated by a 1.5 m area where maize plants were removed between plots. There were approximately 20 plants in each 5 m-row (~40 plants per plot).

The block of maize was then divided into two sub-blocks (Fig. 3.3), each with 24 plots of which the incidence of infestation (%) was determined. Plant stand per plot as well as the number of plants exhibiting whorl damage was recorded four weeks after seedling emergence and the incidence of infested plants per plot calculated. Plants in this trial were subjected to heavy natural infestation which commenced approximately two weeks after seedling emergence. The one sub-block was sprayed with Methomyl® SP (Fig. 3.3) immediately after the incidence of infested plants was determined. This was followed by three additional sprays at weekly

intervals until plant tassels were visible in the whorls. The first application was done during the V6/7 stage to prevent any further larval feeding damage to plants, while the unsprayed sub-block remained unprotected till harvest to allow for continuous larval feeding damage and re-infestation throughout the trial.



Figure 3.3. Photo of maize plants (6 WAE) in trial 3 conducted at Malelane. The plants to the right of the red trial marker were sprayed with insecticide at weekly intervals from the V6/7 growth stage (4 WAE). Larval damage to leaves is conspicuous on the plants which did not receive insecticide applications.

Maize ears of all plants in each plot were harvested and threshed by means of a small ear thresher. Moisture content was analysed and grain mass equivalent at 11% moisture content calculated. The yields of sprayed and unsprayed plots were calculated and expressed as yield per hectare.

3.2.6 Data analysis

Data on the severity of foliar damage (leaf damage score) and yield per plant in the unsprayed blocks were analysed by means of descriptive statistics (Trials 1 and 2). Correlation analyses were done to determine the relationship between damage ratings (2-9 score) and yield loss (Trials 1 and 2). Yield and yield loss of plants that scored different damage rating values in Trials 1 and 2 were expressed as percentage loss in terms of the undamaged plants in these

trials. Yield and yield loss (%) data were subjected to one-way analysis of variance (ANOVA), followed by unequal N HSD at $P = 0.05$. ANOVA was used to compare % yield loss of plants that suffered different degrees of foliar damage (2-9 score).

Yield of the infested plots in Trials 1 and 2 were expressed as a percentage of the uninfested plot yield, for each of the sprayed and unsprayed blocks. In Trial 2, ANOVA was used to compare yield of plots inoculated at different growth stages, followed by Tukey's HSD test. Data on foliar damage rating and yield per plot were analysed by means of one-way ANOVA, followed by Tukey's HSD at $P = 0.05$.

Yield of plants and the mean number of ears per plant infested at different growth stages in Trial 3 were analysed by means of Kruskal-Wallis test followed by Dunn's multiples range test ($P = 0.05$). All analyses were performed with TIBCO Statistica™ 13.3 (TIBCO Software, Inc., 2017).

3.3 Results and discussion

The relationship between severity of damage symptoms and yield loss per plant

Plants that were inoculated with 3rd-instar larvae suffered serious leaf feeding injury as indicated by high leaf damage scores. These high damage scores also indicated successful establishment of inoculated larvae in plant whorls.

The yield of individual plants and their respective damage scores are provided in Figure 3.4. Individual plant yield varied largely, which was especially evident from the yield of uninoculated (undamaged) plants represented by the 1-rating values (Fig. 3.4). The correlation between the severity of damage (2 – 9 score) and plant yield was strong in Trial 1 ($r = 0.70$) and very poor in Trial 2 ($r = 0.13$).

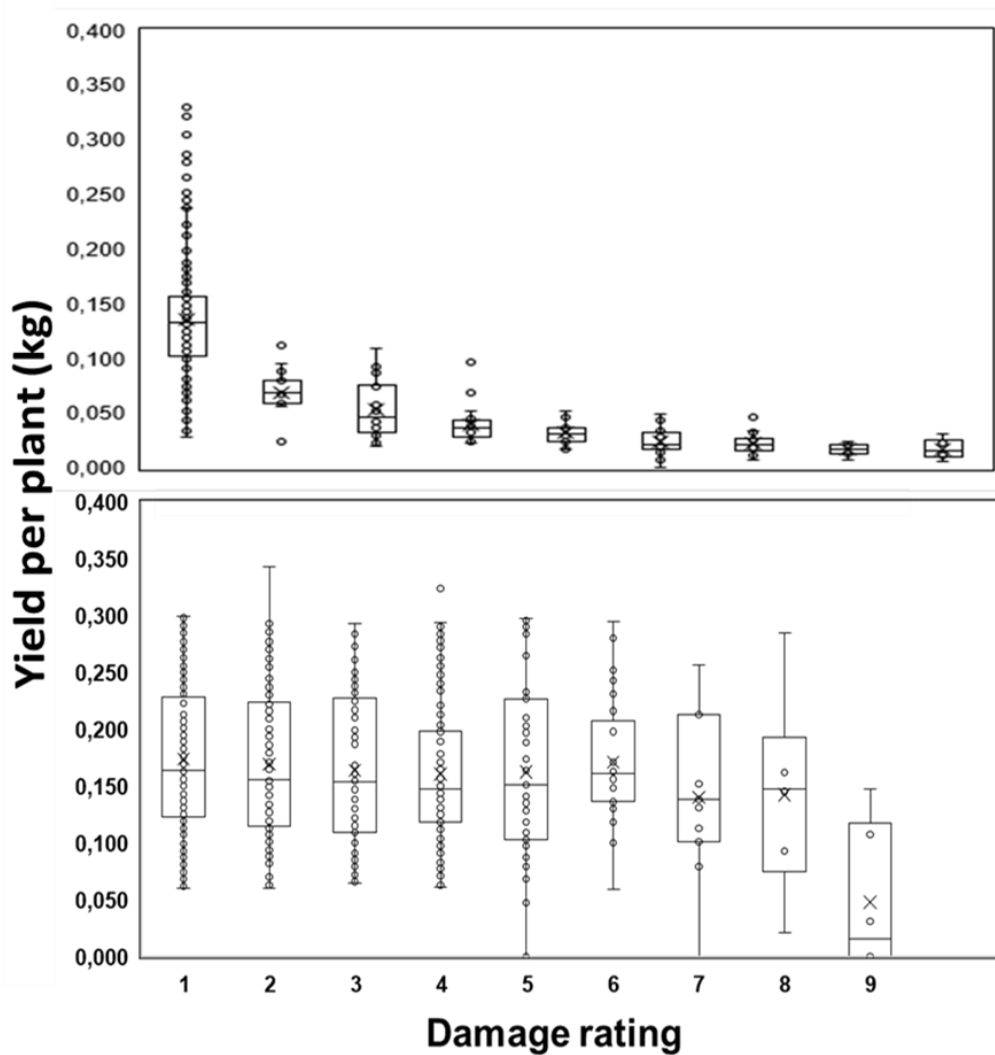


Figure 3.4. Box-and-whisker plots indicating the per plant yield distribution within different categories of leaf damage caused by *Spodoptera frugiperda* larval feeding (above: Trial 1, Below: trial 2). Correlation: Trial 1 ($r = 0.70$); Trial 2 ($r = 0.017$).

Yield of plants that had damage score of 2 – 9 was significantly lower than of those with no damage (i.e. score = 1) (Table 3.3). Yield differed significantly between plants that suffered different degrees of larval feeding damage in Trial 1 ($F = 73.45$; $P = 0.001$) and Trial 2 ($F = 3.34$; $P = 0.001$). Yield loss per plant of plants inoculated during the V6/7 growth stage (Trial 1) and on which larvae completed their life cycles, ranged between 49 and 87%. Yield loss of plants that had a damage rating score of 2 - 4 were significantly lower than that of plants with > 4 scores.

Table 3.3. Mean yield (g) and yield loss per plant (\pm SE) with different degrees of foliar damage caused by *Spodoptera frugiperda* larval feeding in maize plant whorls. In Trial 1 all plants were inoculated at the V4 stage. In Trial 2, plants were inoculated at several growth stages (see 3.2.2).

Rating score	Trial 1		Trial 2	
	Mean yield per plant (g)	Yield loss per plant (%)	Mean yield per plant (g)	Yield loss per plant (%)
1	136.46 \pm 3.70 a	-	173.67 \pm 0.00 a	-
2	69.43 \pm 4.04 b	49.12 \pm 2.96 a	169.19 \pm 0.01 a	2.69 \pm 3.35 a
3	53.19 \pm 4.10 bc	61.02 \pm 3.01 b	163.96 \pm 0.01 ab	1.77 \pm 4.22 a
4	39.55 \pm 3.09 bc	71.02 \pm 2.26 c	160.00 \pm 0.01 ab	1.49 \pm 3.99 a
5	31.99 \pm 1.88 bc	76.56 \pm 1.38 cd	162.00 \pm 0.01 ab	0.37 \pm 5.67 a
6	23.64 \pm 2.59 c	82.68 \pm 1.90 d	171.00 \pm 0.01 a	0.00 \pm 7.52 a
7	22.22 \pm 1.29 c	83.72 \pm 0.95 d	140.00 \pm 0.02 ab	14.28 \pm 12.21 ab
8	17.03 \pm 1.85 c	87.52 \pm 1.36 d	143.00 \pm 0.03 ab	12.95 \pm 16.53 ab
9	17.24 \pm 3.63 c	87.37 \pm 2.66 d	48.00 \pm 0.03 b	70.69 \pm 16.53 b

Means within columns followed by the same letters do not differ significantly at $p < 0.05$).

Plants that were inoculated at different growth stages and had damage scores of 2 – 6 did not suffer any significant yield losses. Only at a damage score of 7 did higher losses start to occur and only at a score of 9, were losses significantly higher than those of plants with other damage scores. Plants that exhibited low damage scores (2-5) were damaged by larvae that moved from the natal infested plants to neighbouring plants, which is natural behaviour of FAW larvae. This also shows that larvae did move from the natal plant to other plants over the approximate seven days from 3rd instar to when they would reach the 6th instar and become pupae. Carvalho and Silveira (1971) also reported that interplant larval movement leads to high incidences of plants that exhibit damage symptoms, other than those that were inoculated or on which eggs were laid, and indicated that many of the plants would have had only one or two larvae in their whorls. The data collected from these field trials is representative of what would happen under field conditions. Larval migration to neighbouring plants takes place to avoid competition which allows only few larvae per maize whorl throughout the cropping system (>80%) (Buntin 1986). Nutrient requirements of sixth-instar larvae are greater than in

any other instar so as to allow for accumulation of sufficient amount of energy reserves for pupation. This drastically leads to an increase in the consumption of foliar tissues and results in high yield losses (Linduska and Harrison 1986).

The contrasting responses of plants to larval damage observed in Trials 1 and 2 illustrates the complexity of this injury – damage – loss relationship. Plant response to damage is not only influenced by the severity of the symptoms, but also by factors such as drought conditions, nutrient status of the soil, the duration of the larval feeding period, number of larvae per plant and inherent level of plant resistance to larval feeding damage.

The Davis 1-9 rating scale was not developed as indicator of plant response to FAW damage, or estimator of yield. The purpose of this rating scale was to identify maize breeding lines with resistance to FAW larvae. The rating scale was developed to identify small differences in levels of plant resistance (antibiosis and antixenosis) to FAW larvae.

Brown and Mohamed (1972) reported that maize plants were able to tolerate severe foliar damage, especially during the early vegetative stages. This is ascribed to young plants being able to recover from foliar damage during the vegetative developmental stages before tassel formation and ear development (Buntin 1986).

3.3.1 Field Trial 1: The relationship between infestation level (incidence (%) of damaged plants) and yield

Plot yield, expressed as a percentage of the yield of the inoculated control treatment, and therefore presented as corrected plot yield, ranged between 83.9% for plots with 10% infested plants (unsprayed), to 26.2% for plots in which all plants were inoculated with FAW larvae (unsprayed) (Fig. 3.5). However, the corrected percentage yield per plot did not differ regardless of the infestation level where insecticides were applied to control larvae 7 days after inoculation. Significant yield losses were recorded at infestation levels higher than 20%. Yield was negatively correlated with levels of FAW infestation in the unprotected sub-plot (Fig 3.6).

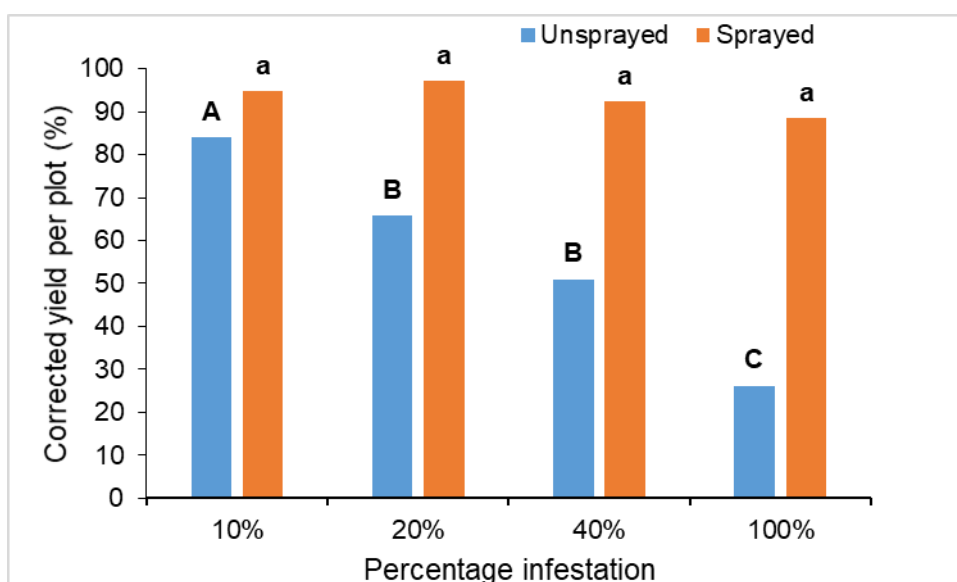


Figure 3.5. Yield of plots with different infestation levels (% plants), expressed as a percentage of the yield (corrected yield) of uninoculated plots. Plants were inoculated with *Spodoptera frugiperda* larvae during the V4 stage (Trial 1). Blue bars indicate plot yield without insecticide application one week after inoculation, while the orange bars indicate plot yield when insecticide was applied into the whorls of plants, one week after artificial inoculation. Similar uppercase letters, for the unsprayed treatments, and lowercase letters, for the sprayed treatments, above bars indicate that differences were not significant between infestation levels ($P < 0.05$).

The severity of damage is highly influenced by the vulnerability of different growth stages of maize plants, the level of FAW infestation and the instar of FAW larvae which feed within maize whorls (Fenimore 1982; Gross *et al.* 1982; Harrison 1984; Buntin 1986; Linduska and Harrison 1986; Ortega 1987; Flanders *et al.* 2017). Low levels of plant injuries are inflicted by first-instar larvae, which are present in high numbers after they have hatched. The degree of damage caused by these small larvae is limited to pinhole and small lesion damage and in itself does not result in yield loss (Linduska and Harrison 1986; Hardke *et al.* 2011) and foliar injuries inflicted by early-instar larvae are not easily detected or visible (Prasanna *et al.* 2018). Effective chemical control of 1st – 3rd instar larvae can be obtained by means of insecticide application but in order to facilitate early-enough application, monitoring of damage and the incidence of infestation inside fields are required. Regular and intensive scouting should be done to detect the presence of FAW larvae within maize fields (Linduska and Harrison 1986; Prasanna *et al.* 2018).

Results from this trial is representative of a scenario where there is only a single infestation of the crop and therefore a limited period during which larvae damage the plants before they become pupae. Kuate *et al.* (2019) reported a significant positive correlation between the incidence of infested plants within a maize field and the severity of damage symptoms and subsequent yield loss. Observations in Cameroon indicated that, at the field level, there was a positive correlation between incidence and severity. Larvae are known to disperse between plants from the egg mass after hatching and severe damage could result from initial feeding by several larvae; however, at later developmental stages (5th and 6th -instar), only one larva is usually observed per plant (Kuate *et al.* 2019).

3.3.2 Trial 2: The effect of plant growth stage at time of inoculation on yield loss

The yield of individual plants and their respective damage scores are provided in Figure 3.6. Individual plant yield varied largely, which was especially evident from the yield of uninoculated (undamaged) plants represented by the 1-rating values.

Yield did not differ between plots that were inoculated at different plant growth stages and did not also differ significantly between infested plants at the growth stages V4, V7, V10 and Boot stage ($H = 5.00$; $P = 0.287$).

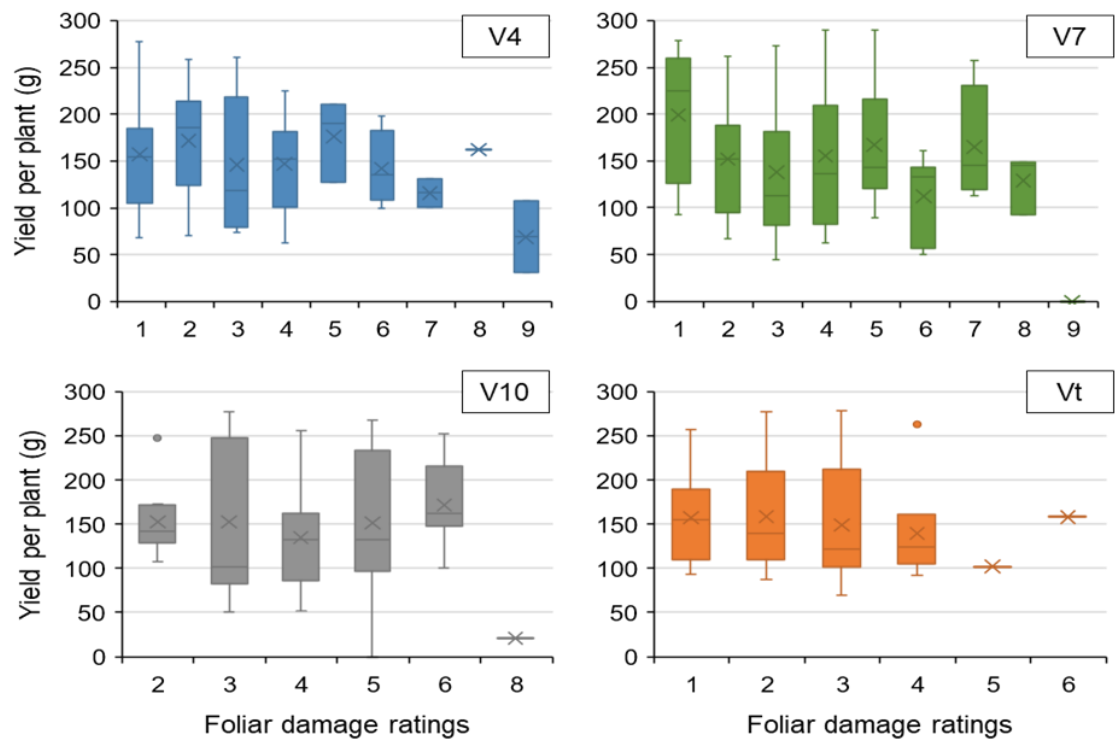


Figure 3.6. Box and whisker plots indicating the per plant yield distribution within different categories of leaf damage caused by *Spodoptera frugiperda* larval feeding on plants inoculated with three 3rd-instar larvae at different growth stages. Undamaged plants are represented by the 1-rating value, while the other ratings represent plants with different levels of damage. Growth stages (V4-Vt), Vt = Boot stage.

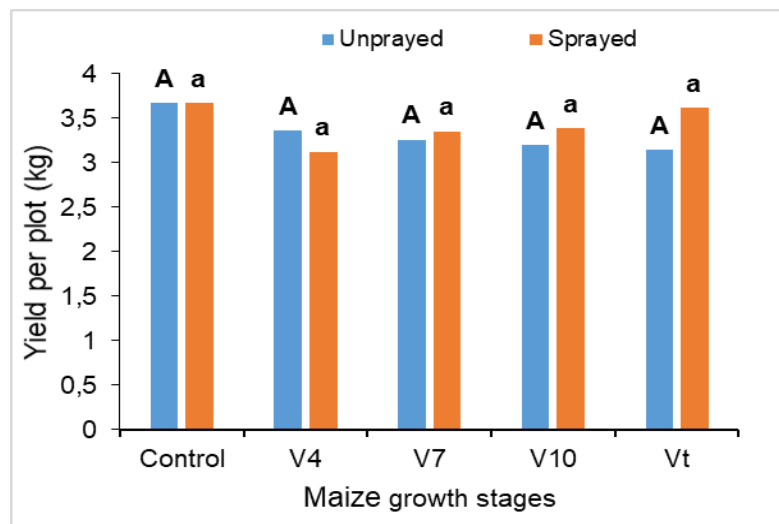


Figure 3.7. Maize plot yield after infestation of all plants per plot with 3rd instar *Spodoptera frugiperda* larvae at different plant growth stages, when no insecticide application was done and when insecticide was applied seven days later. Similar uppercase letters, for the unsprayed treatments, and lowercase letters, for the sprayed treatments, above bars indicate that differences were not significant between treatments ($P < 0.05$).

Results of this study, in which only a single inoculation with larvae was done at different growth stages, showed no significant differences between plant susceptibility to FAW at different growth stages. Other authors reported that plants differed in their susceptibility at different stages. Buntin (1986) reported that yield was most affected when infestation of FAW larvae took place during tassel formation of maize even though only little foliar damage symptoms may result from such a late infestation. After tassel formation, FAW larvae start to feed on the developing maize ears (Morrill and Greene 1973) or the leaf bases (Wiseman *et al.* 1967). These plant structures which are directly involved in yield production therefore, increasing the susceptibility of maize plants to damage during this growth stage (Morrill and Greene 1973; Buntin 1986). Although this was not the case in this study, serious infestations during the boot and tassel stage, as described by Buntin (1986) would necessitate insecticide application during the boot stage.

Results from this trial are representative of a scenario where there is only a single infestation of the crop at a particular growth stage and where no reinfestations occur. Larvae under such conditions therefore have a limited period during which they damage plants before they become pupae.

The level of tolerance expressed by host plants is directly related to the rate of cell replication, thus the rate of recovery (Nelissen *et al.* 2012, 2015). The rates at which plants grow forms part of complex interactions with their environment which either suppress or promote the expression of growth hormones within the individual plant (Nelissen *et al.* 2012, 2015). Plant growth occurs through the process of cell division and elongation that are initiated by high concentrations of gibberellic acid (GA), cytokinins and auxins (Nelissen *et al.* 2012). These hormones are produced within the apical meristems of roots and stems, respectively (Nelissen *et al.* 2012), and their expressed levels of concentration are negatively correlated with the growth stages of maize plants. High levels of susceptibility expressed during the Boot stage are not due to direct damage to the tassel itself but as a result of extensive foliar damage to the leaves that cover the tassel (Gross *et al.* 1982) and damage to the developing ears (Morrill and Greene 1973). On the other hand, young plants at early vegetative stages are able to compensate for damage inflicted by FAW larvae with high cell replication rates (Nelissen *et al.* 2012).

Mean damage rating per plot ranged between 3.0 and 4.1 for plants that were inoculated during the vegetative stages while it was lower for plants inoculated during the boot stage (2.2) (Fig. 3.8). Although there was a tendency that insecticide application, 7 days after inoculation, reduced the severity of leaf damage, this was not significant (Fig. 3.8).

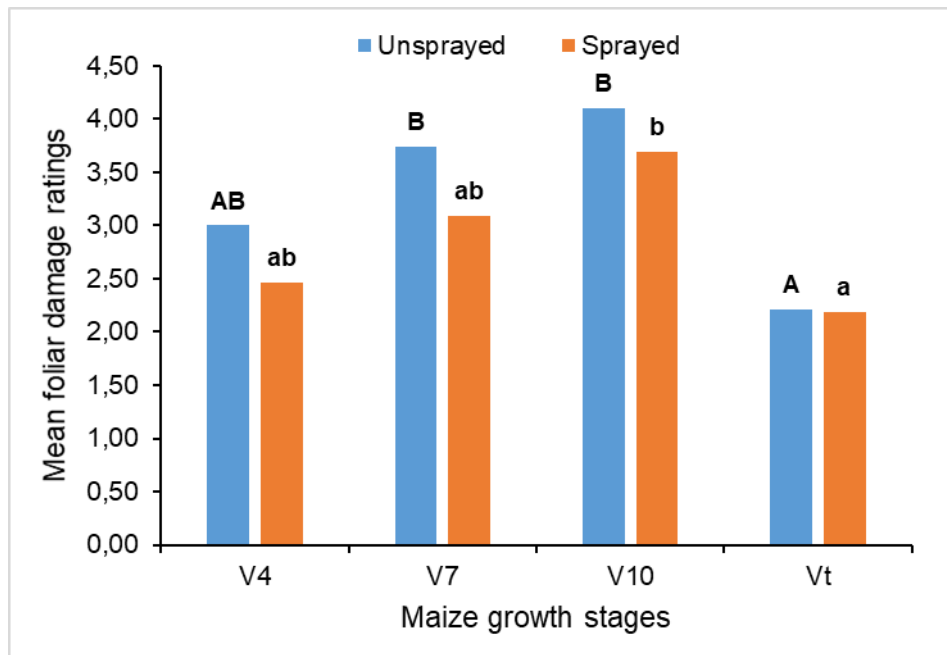


Figure 3.8. Mean leaf damage scores per plot of maize plants artificially inoculated with three 3rd instar *Spodoptera frugiperda* larvae per plant at different plant growth stages when no insecticide application is done (blue bars) and when insecticide is applied (orange bars) seven days later. Similar uppercase letters, for the unsprayed treatments, and lowercase letters, for the sprayed treatments, above bars indicate that differences were not significant between treatments ($P < 0.05$).

The rating scores were lowest for plants inoculated at the stage when tassels started to appear. The lower foliar damage score when plants were inoculated during the boot stage is ascribed to FAW larvae that change their feeding site from the whorl leaves of maize plants to the silks and developing ears, therefore resulting in direct yield losses via damage infliction to maize ears (Wiseman *et al.* 1967; Morrill and Greene 1973). Maize plants infested at the V10 leaf stage had significantly higher damage ratings than maize plants infested at the Boot stage, but not 2 and 4 weeks after emergence at the V4 and V7 leaf stage, respectively (Fig. 3.8). Insecticide application had a negligible effect on damage rating if applied a week after inoculation, except for the application on 7 weeks after emergence (one week after Boot stage).

The mean number of ears per plant did not differ significantly ($P = 0.206$) between plants that were inoculated at the different growth stages. This is in accordance with results reported by Cruz and Turpin (1983) that FAW damage does not negatively affect the number of ears produced but rather the mean ear length which results in the lower yield.

The V4 stage (2 weeks after emergence) and boot stage (8 weeks after emergence) of maize plants are most susceptible to FAW infestation and infestations during this stage would result in the greatest yield and economic losses (Fig. 3.8). Therefore, intensive scouting is required just prior to and during this growth stage to monitor FAW infestation and damage levels present within the maize field. Chemical control should be implemented during this growth stage if supported by the data provided above.

3.3.3 Trial 3: The effect of different levels of FAW infestation and insecticide application on yield

The incidence of plants that showed FAW larval feeding damage per plot at 4 WAE is indicated in Table 3.4. Infestation levels ranged between 33 and 93% and the mean percentage of infested plants for the block was 65%.

Table 3.4. The incidence (%) of maize plants per plot that exhibited *Spodoptera frugiperda* larval feeding damage, 4 weeks after seedling emergence at the Malelane trial site (Trial 3).

Treatments							
Block 1: Unsprayed				Block 2: Sprayed			
Plot 1	Plot 2	Plot 3	Plot 4	Plot 1	Plot 2	Plot 3	Plot 4
70	72	88	73	57	54	86	86
79	69	83	65	73	49	62	55
76	51	69	76	65	60	93	77
69	55	57	76	65	53	33	52
59	56	62	38	73	64	70	51
53	58	88	77	48	51	69	58

The relationships between incidence of plants with FAW damage to whorl leaves and yield is presented in Figure 3.9 and 3.10. There was a slight but significant relationship ($r = 0.51$; $F = 7.613$; $P = 0.011$) between the incidence of damaged plants and yield in the plots where insecticides were applied to stop larval feeding damage from 4 WAE onwards. There was no significant relationship between the incidence of infested plants at 4 WAE and yield at the time of harvest ($r = 0.12$; $F = 0.325$; $P = 0.57$). This means that the % of infested plants during mid-vegetative growth stages, such as the scenario in this study, is not a good predictor of eventual yield loss. The significant yield gain obtained in plots of all different infestation levels in the

protected sub-plot, indicated that it may be more appropriate to base a decision on insecticide application on the plant growth stages that need protection, than the infestation level. In other words, percentage infested plants did not provide a clear indication of eventual yield loss in this study.

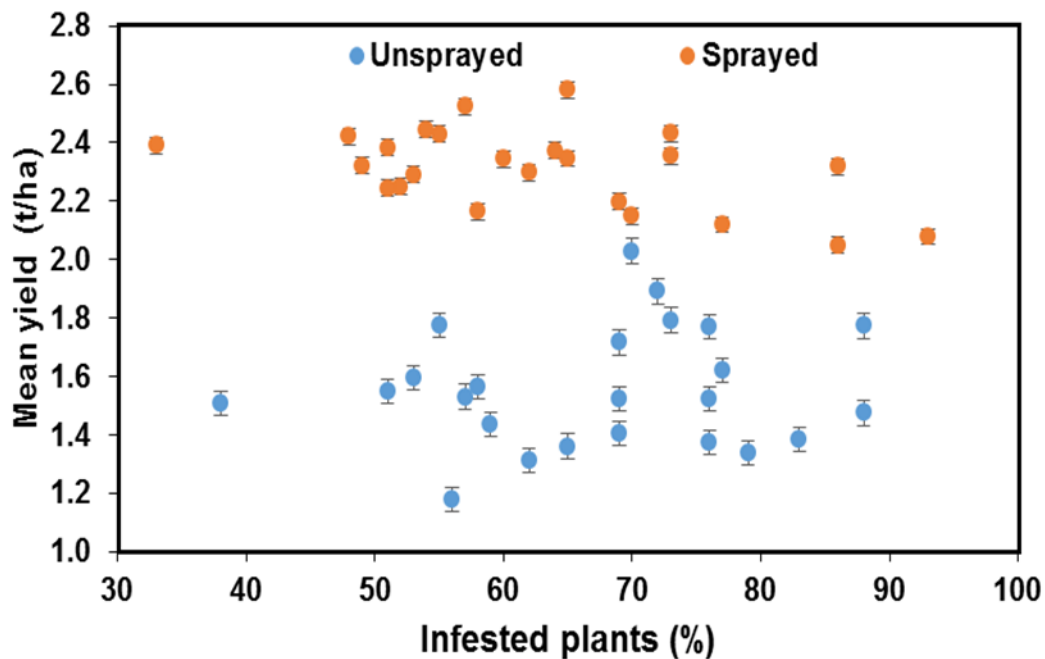


Figure 3.9. A scatterplot indicating the incidence (%) of infested plants per plot and yield (expressed per hectare), of a field trial under natural infestation by *Spodoptera frugiperda*. Bars represent Standard Errors.

Yield obtained within a given plot is not directly related to the percentage of maize plants that exhibit whorl and furl damage but is rather influenced by the severity of foliar damage observed (Fig 3.9). The numbers of FAW larvae within a given maize field decreases as they develop into later-instars (Carvalho and Silveira 1971) due to unfavourable environmental conditions, presence of predatory insects, as well as competition and cannibalism among them (Carvalho and Silveira 1971; Prasanna *et al.* 2018). High numbers of small-instar larvae do not inflict conspicuous damage symptoms and this damage remains undetected in most maize plants (Linduska and Harrison 1986; Hardke *et al.* 2011; Prasanna *et al.* 2018). Therefore, since these damage symptoms go unnoticed, no control measures are implemented, which allows for larvae to fully develop and inflict maximum damage. Chemical control at these late stages

is also not effective (Linduska and Harrison 1986; Hernandez-Mendoza *et al.* 2008; Hardke *et al.* 2011; Flanders *et al.* 2017).

Regression analyses conducted on the data from the field trial (Fig. 3.10) under high natural pest pressure showed interesting tendencies. The regression lines indicating that the yield of sprayed (red) and unsprayed (black) plots differed significantly with significant yield gains resulting from protection of plants from 4 WAE onwards. Repeated infestations of plants in this trial took place and this scenario may therefore be representative of typical maize farming systems in sub-tropical and tropical areas in Africa. The largest yield gains were obtained with insecticide applications on plots that had between 45 and 60% infested plants (arrows B and C, respectively). These results are, however, only from a single cropping season and careful interpretation together with further experimentation is needed.

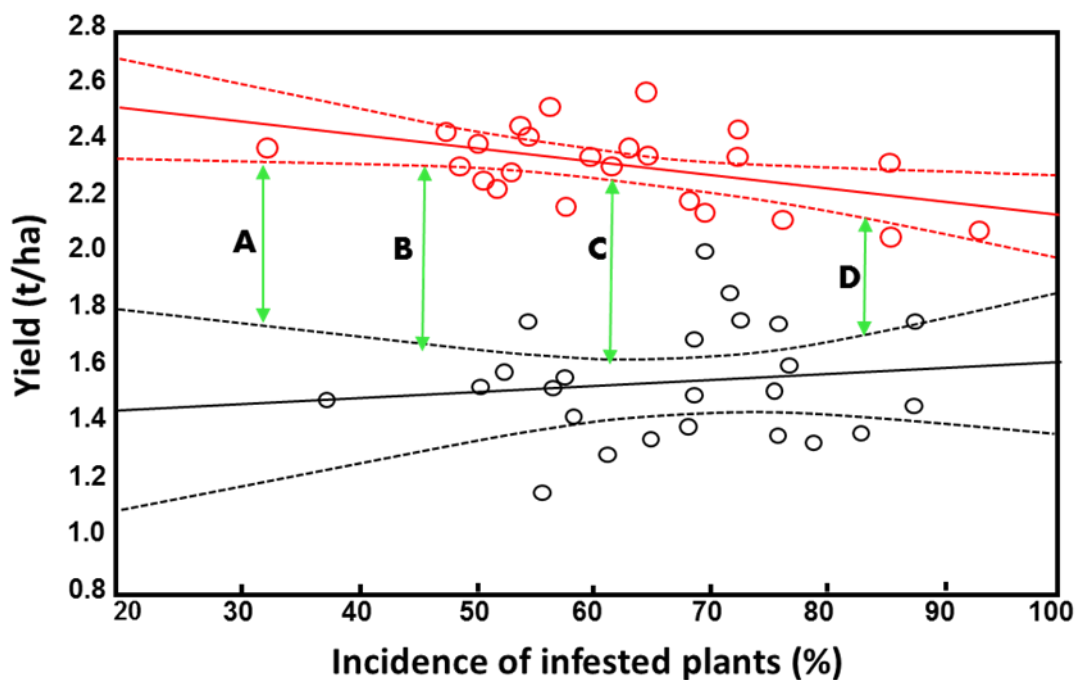


Figure 3.10. Regression lines indicating the relationships between incidence of plants with FAW damage to whorl leaves and yield. Red lines = sprayed plots; black lines = unsprayed plots. Dotted lines represent 95% confidence intervals. Green arrows (A – D) indicate varying distances between the confidence interval lines.

Linduska and Harrison (1986) and Prasanna *et al.* (2018) suggested that implementation of chemical control should be done when 40% of maize plants exhibit visible damage symptoms, irrespective of the severity of damage. The latter authors indicated chemical control at that

stage would be feasible and comparatively more effective since small instar larvae will largely be present, and these are easily controlled by means of foliar applications. Hardke *et al.* (2011) suggested that chemical control should be applied before damage has risen to 40% of maize plants in a particular field.

3.4 Conclusions

The relationship between FAW damage and eventual yield loss is complicated and influenced by many factors. Results of this study showed that the severity of larval damage to plants (2-9 scores) were poorly correlated to yield loss and that the severity of damage symptoms was not a good indicator of how plants would respond to damage, especially if plants were infested at early stages and there was time for them to recover from damage. While the results discussed above showed that plant growth stage at the time of infestation did not influence yield loss, it did show that the level of infestation (% plants) had a significant effect on yield, if no chemical control was applied.

3.5 References

- ABRAHAM, P., BATEMAN, M., BEALE, T., CLOTTEY, V., COCK, M., COLMENAREZ, Y., CORNIANI, N., DAY, R., EARLY, R., GODWIN, J.L., *et al.* 2017. Fall Armyworm: Impacts and Implications for Africa; Evidence Note (2); CABI: Oxfordshire, UK, September 2017.
- AGUIRRE, L.A., HERNANDEZ-JUAREZ, A., FLORES, M., CERNA, E., LANDEROS, J., FRIAS, G.A. and HARRIS, M.K. 2016. Evaluation of foliar damage by *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to genetically modified corn (Poales: Poaceae) in Mexico. *The Florida Entomologist* 99: 276-280.
- BAUDRON, F., ZAMAN-ALLAH, M.A., CHAIPA, I., CHARI, N. and CHINWADA, P. 2019. Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* JE Smith) damage in African smallholder maize fields and quantifying its impact on yield: a case study in eastern Zimbabwe. *Crop Protection* 120: 141-150.
- BROWN, E.S. and MOHAMED, A.K.A. 1972. The relation between simulated armyworm damage and crop-loss in maize and sorghum. *The East African Agricultural Journal* 37: 237-257.

- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- CARVALHO, R.P.L. and SILVEIRA, N.S. 1971. Observacoes do comportamento de *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera, Noctuidae) ao atacar milho em condicoes de campo. *In Resumen del Congreso Latinoamericano de Entomologia 1*: Cuzco, Peru. pp. 88-90.
- CRUZ, I. and TURPIN, F.T. 1983. Yield impact of larval infestations of the fall armyworm (Lepidoptera: Noctuidae) to midwhorl growth stage of corn. *Journal of Economic Entomology* 76: 1052-1054.
- DAVIS, F.M. NG, S.S and WILLIAMS, W.P. 1992. Visual rating scale for screening whorl-stage corn for resistance to fall armyworm. Published by the Department of Information Services, Division of Agriculture, Forestry, and Veterinary Medicine, Mississippi State University, MS, USA. 10 pp.
- DAY, R., ABRAHAMS, P., BATEMAN, M., BEALE, T., CLOTTEY, V., COCK, M., COLMENAREZ, Y., CORNIANI, N., EARLY, R., GODWIN, J., GOMEZ, J., MORENO, P.G., MURPHY, S.T., OPPONG-MENSAH, B., PHIRL, N., PRATT, C., SILVESTRI, S. and WITT, A. 2017. Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management* 196-201.
- FENEMORE, P.G. 1982. Plant pests and their control. Wellington, NZ: Butterworths. 271p. ISBN 0-409-60087-3.
- FLANDERS, K.L., BALL, D.M. and COBB, P.P. 2017. Management of FAW in pastures and hay fields. The Alabama Cooperative Extension System (Alabama A&M University and Auburn University). pp. 8.
- GOERGEN, G., KUMAR, P.L., SANKUNG, S.B., TOGOLA, A. and TAMO, M. 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in west and central Africa. *PLoS ONE*. DOI: 10.1371/journal.pone.0165632.
- GROSS JR, H.R., YOUNG, J.R. and WISEMAN, B.R. 1982. Relative susceptibility of a summer-planted dent and tropical flint corn variety to whorl stage damage by the Fall armyworm (Lepidoptera: Noctuidae). *Journal of Economic Entomology* 75: 1153-1156.
- HARDKE, J.T., TEMPLE, J.H., LEONARD, B.R. and JACKSON, R.E. 2011. Laboratory toxicity and field efficacy of selected insecticides against fall armyworm (Lepidoptera: Noctuidae). *Florida Entomologist* 94: 272-278.

- HARRISON, F.P. 1984. The development of an economic injury level for low populations of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 67: 335-339.
- HARRISON, R.D., THIERFELDER, C., BAUDRON, F., CHINWADA, P., MIDEGA, C., SCHAFFNER, U and VAN DEN BERG, J. 2019. Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management* 243: 318-330.
- HERNANDEZ-MENDOZA, J.L., LOPEZ-BARBOSA, E.C., GARZA-GONZALEZ, E. MAYEK-PEREZ, N. 2008. Spatial distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize landraces grown in Colima, Mexico. *International Journal of Tropical Insect Science* 28: 126-129.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CAB Reviews* 14: 1-11.
- HRUSKA, A.J. and GLADSTONE, S.M. 1988. Effect of period and level of infestation of the fall armyworm, *Spodoptera frugiperda*, on irrigated maize yield. *The Florida Entomologist* 71: 249-254.
- HRUSKA, A.J. and GOULD, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology* 90: 611-622.
- KUATE, A.F., HANNA R., DOUMTSOP FOTIO, A.R.P., ABANG, A.F., NANGA, S.N., NGATAT, S., TINDO, M., MASSO, C., NDEMAH, R., SUH, C. and FIABOE, K.K.M. 2019. *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Cameroon: Case study on its distribution, damage, pesticide use, genetic differentiation and host plants. PLoS ONE 14: e0215749. <https://doi.org/10.1371/journal.pone.0215749>
- KUMELA, T., SIMIYU, J., SISAY, B., LIKHAYO, P., MENDESIL, E., GOHOLE, L. and TEFERA, T. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management* 1-9.
- LIANG, J., TANG, S. and CHEKE, R.A. 2012. An integrated pest management model with delayed responses to pesticide applications and its threshold dynamics. *Nonlinear Analysis: Real World Applications* 13: 2352-2374.

- LIMA, M.S., SILVA, P.S.L., OLIVEIRA, O.F., SILVA, K.M.B. and FREITAS, F.C.L. 2010. Corn yield response to weed and fall armyworm controls. *Planta Daninha, Viscosa-MG* 28: 103-111.
- LINDUSKA, J.J and HARRISON, F.P. 1986. Adult sampling as a means of predicting damage levels of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 69: 487-491.
- MORRILL, W.L. and GREENE, G.L. 1973. Distribution of fall armyworm larvae. Influence of biology and behavior of larvae on selection of feeding sites. *Environmental Entomology* 2: 415-418.
- NELISSEN, H., RYMEN, B., JIKUMARU, Y., DEMUYNCK, K., VANA LIJSEBETTENS, M., KAMIYA, Y., INZA, D. and BEEMSTER, G.T.S. 2012. A local maximum in gibberellin levels regulates maize leaf growth by spatial control of cell division. *Current Biology* 22: 1183-1187.
- NELISSEN, H., EECKHOUT, D., DEMUYNCK, K., PERSIAU, G., WALTON, A., VAN BEL, M., VERVOORT, M., CANDAELE, J., DE BLOCK, J., AESAERT, S., VANA LIJSEBETTENS, M., GOORMACHTIG, S., VANDEPOELE, K., VAN LEENE, J., MUSZYNSKI, M., GEVAERT, K., INZE, D. and DE JAEGER, G. 2015. Dynamic changes in angustifolia3 complex composition reveal a growth regulatory mechanism in the maize leaf. *The Plant Cell* 27: 1605-1619.
- ORTEGA, C.A., 1987. Insect pests of maize: a guide for field identification [Internet]. Mexico: CIMMYT. Available: <https://repository.cimmyt.org/xmlui/handle/10883/700>.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014a. Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks. *Physics of life reviews* 11: 467-525.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014b. Multiscale ecology of agroecosystems is an emerging research field that can provide a stronger theoretical background for the integrated pest management. Reply to comments on "Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks". *Physics of life reviews* 11: 536-539.
- PRASANNA, B.M., HUESING, J.E., EDDY, R. and PESCHKE, V.M. (eds). 2018. Chapter 4. Host plant resistance to fall armyworm. P53. In: *Fall Armyworm in Africa: A Guide for Integrated Pest Management*, 1st ed. Mexico, CDMX: CIMMYT.

SISAY, B., TEFERA, T., WAKGARI, M., AYALEW, G. and MENDESIL, E. 2019. The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda*, in maize. *Insects* 10: 1-14. doi:10.3390/insects10020045.

TIBCO Software, Inc. 2017. TIBCO Statistica™ 13.3. 1984-2017.

VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.

WISEMAN, B.R., WASSOM, C.E. and PAINTER, R.H. 1967. An unusual feeding habit to measure differences in damage to 81 Latin-american lines of corn by the fall armyworm, *Spodoptera frugiperda* (J. E. Smith). *Agronomy Journal* 59: 279-281.

Chapter 4

The effect of protection of maize plants during certain growth stages on yield losses caused by *Spodoptera frugiperda*

Abstract

Fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is a major pest of maize in Africa and the Americas. Yield losses due to FAW have been reported to be between 30 and 70% in the Americas and 11 and 100% in Africa. Previous studies have shown that insecticide applications at weekly intervals did not always provide higher yields compared to only a single or two well-timed applications. Although insecticides are commonly applied for FAW control, little information exists on the effect of pest damage during different plant growth stages on yield loss. Three field trials of 16 treatments in a randomized complete block design were planted at localities with high natural FAW pressure. Treatments were divided into two spray sequences to protect plants against FAW damage for different lengths of time, between early-vegetative stages to tasselling. The upper check treatment received insecticide treatments at weekly intervals from two weeks after seedling emergence up to the boot stage. Yield was determined for each plot. Yield losses were 41.9, 26.5 and 56.8% for the three respective trials if no insecticides were applied. More than three spray applications generally did not provide further yield gains. Plots in which plants were protected more during early growth stages produced higher yields than those protected during later growth stages.

Key words: Damage severity; Injury; Insecticide application

4.1 Introduction

Fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is a primary pest of maize in Africa because of its destructive feeding habits on foliage and ears of maize during the reproductive stage (Day *et al.* 2017). This damage results in both quantitative and qualitative losses (Cruz and Turpin 1983; Lima *et al.* 2010; Day *et al.* 2017).

FAW infests maize during all plant growth stages with infestation during vegetative stages leading to serious leaf feeding injury while late infestations lead to ear damage (Fenemore 1982; Gross *et al.* 1982; Harrison 1984; Buntin 1986; Ortega 1987; Hardke *et al.* 2011; Kuate *et al.* 2019). Ear damage can lead to fungal infections and mycotoxin production (Gorman and Kang 1991; Pruter *et al.* 2019). FAW damage to maize plants during the late growth stages, just prior to tassel emergence, may result in ear damage and comparatively higher yield losses (Wiseman *et al.* 1967; Morrill and Greene 1973, 1974; Gross *et al.* 1982; Buntin 1986). On the other hand very early infestations, especially during the seedling stages, can lead to total defoliation and crop loss (Buntin 1986; Silva-Aguayo *et al.* 2010). Yield losses suffered by maize plants are therefore mostly dependent on plant tissue type where larval damage occurs (Buntin 1986), with infestations during the vegetative growth stages leading to extensive foliar damage. Brown and Mohamed (1972), however, reported that maize plants are able to tolerate foliar damage when injured during younger vegetative stages.

Insecticide applications have been the main method of FAW control in South America (All *et al.* 1986; Pina and Solleiro 2013) and in Africa since its arrival in 2016 (Goergen *et al.* 2016; DAFF 2017; Day *et al.* 2017; Sisay *et al.* 2019). The application of insecticides usually provides inadequate control of this pest (Hardke *et al.* 2011). Chemical control strategies are only effective when larvae are small and require timely or regular applications (Yu 1991; Hardke *et al.* 2011). Insecticide applications against FAW in maize are often reported to be not as effective due to incorrect application methods, cryptic feeding behaviour of larvae and application of insecticides when larvae are too large and not susceptible anymore (Hardke *et al.* 2011; Day *et al.* 2017; Rwomushana *et al.* 2018). However, efficacy of insecticides applied at high rates against FAW has been reported to be rapid and efficient, compared to other control measures, if these applications are done timeously and correctly (All *et al.* 1986; Pina and Solleiro 2013; Sisay *et al.* 2019). Short generation periods, which can be completed within 20 - 30 days, may result in re-infestation of the same crop by *S. frugiperda*, resulting in a need for repeated insecticide applications, which may lead to resistance evolution against insecticides (Day *et al.* 2017; Rwomushana *et al.* 2018). Field-evolved resistance to insecticides have been reported in Puerto Rico and several other countries (Yu 1991; Gutiérrez-Moreno *et al.* 2018). Repeated pesticide applications against FAW infestations on

maize have been reported by many authors (All *et al.* 1986; Pina and Solleiro 2013; Day *et al.* 2017; Sisay *et al.* 2019).

It is important to estimate the effects of insecticide application at different growth stages under African conditions since the protection that these applications provide to plants for certain periods may have significant yield benefits (Van Huis 1981; Buntin 1986; Andrews 1988). It is important to identify the duration of the period of protection that would result in significant yield gains (Van Huis 1981; Buntin 1986; Andrews 1988), based on the infestation levels observed in maize fields (Hruska and Gould 1997; Hruska 2019).

For chemical control to be economical, it must be applied according to an ETL carefully determined for each specific pest species (Hruska 2019). However, most literature from North and South America indicate no to poor correlations between the level of FAW infestation, foliar damage and actual yield loss. No data on damage – yield loss relationships are, however, available from Africa. Several authors reported losses between 17% and 30% (Galt and Staton 1979), with occasional losses as high as 100% (Silva-Aguayo *et al.* 2010). However, Montenegro (1981) stated that foliar feeding did not affect yield of maize in Brazil. Literature provides contradicting results on whether chemical control of FAW is effective so as to reduce yield loss. Del Rosario *et al.* (1981) and Del Rosario and Diclo (1981) stated that chemical control of FAW in Dominican Republic was economically justifiable with significantly higher yields recorded in sprayed fields. Chemical application was also justified in southern parts of North America and South America (Ryder 1968; Sifuentes 1978; Silva-Aguayo *et al.* 2010). Reports also indicated that implementation of control measures against FAW larvae may only provide small yield gains (Del Rosario *et al.* 1981; Del Rosario and Diclo 1981). For these reasons, chemical control is most of the time not economically justifiable and implementation of good agricultural practices, especially application of the correct fertilizers (van Huis 1981) and the use of agroecological methods (Harrison *et al.* 2019), are usually sufficient to improve plant health and to make plants more tolerant to damage. Improved knowledge on plant response to FAW damage can contribute to the estimation of an ETLs for FAW which will contribute to a decision support systems for improved FAW management.

The aims of this study were to determine the effect of a single very early and a very late insecticide application, as well as repeated foliar applications from two weeks after seedling emergence to early tassel formation (boot stage), on yield and yield loss caused by FAW in maize.

4.2 Materials and methods

Three field trials were established during the 2018/19 growing seasons. Trials 1 and 2 were conducted on adjacent fields at an experiment farm in Malelane, South Africa and Trial 3 at an experimental farm in Nelspruit, South Africa. Sub-tropical climatic conditions allowed for natural FAW infestation of maize plants throughout the season at all three sites.

4.2.1 Trials 1 and 2

Two plantings of each trial were planted in February 2019 (5th and 12th). Each planting consisted of 10 to 15 rows, 100 m in length at a 1.0 m inter-row and 1.5 m intra-row spacing. The experimental design adopted for each trial was a randomised complete block of 16 treatments in four replicates. For both Trial 1 and 2 each treatment plot consisted of two 5 m long rows. Each plot contained approximately 40 plants.

The first insecticide applications were done one week after seedling emergence in both trials.



Figure 4.1. Left: Trial 1 (1 WAE), indicated by the trial markers and yellow line, and trial 2, indicated by the blue line and with seedlings starting to emerge (not visible on photograph). Right: Photograph of plants in Trial 1 at 3 WAE.

4.2.2. Trial 3

This trial had a similar layout and design as those described for Trials 1 and 2. This trial was however, planted on 20th of February 2019 and consisted of 10 rows, 150 m in length with a 1.2 m inter-row spacing. The 16 treatments were replicated each five times, with each replicate consisting of a single row of 5 m in length.

The treatments were identical to those indicated in Table 4.1. This trial also received its first insecticide application one week after seedling emergence. However, due to this site being at a higher altitude than for Trials 1 and 2, the plant developmental period was prolonged at this site. This was ascribed to lower temperatures, especially during night times, and humidity which was lower than at Malelane.

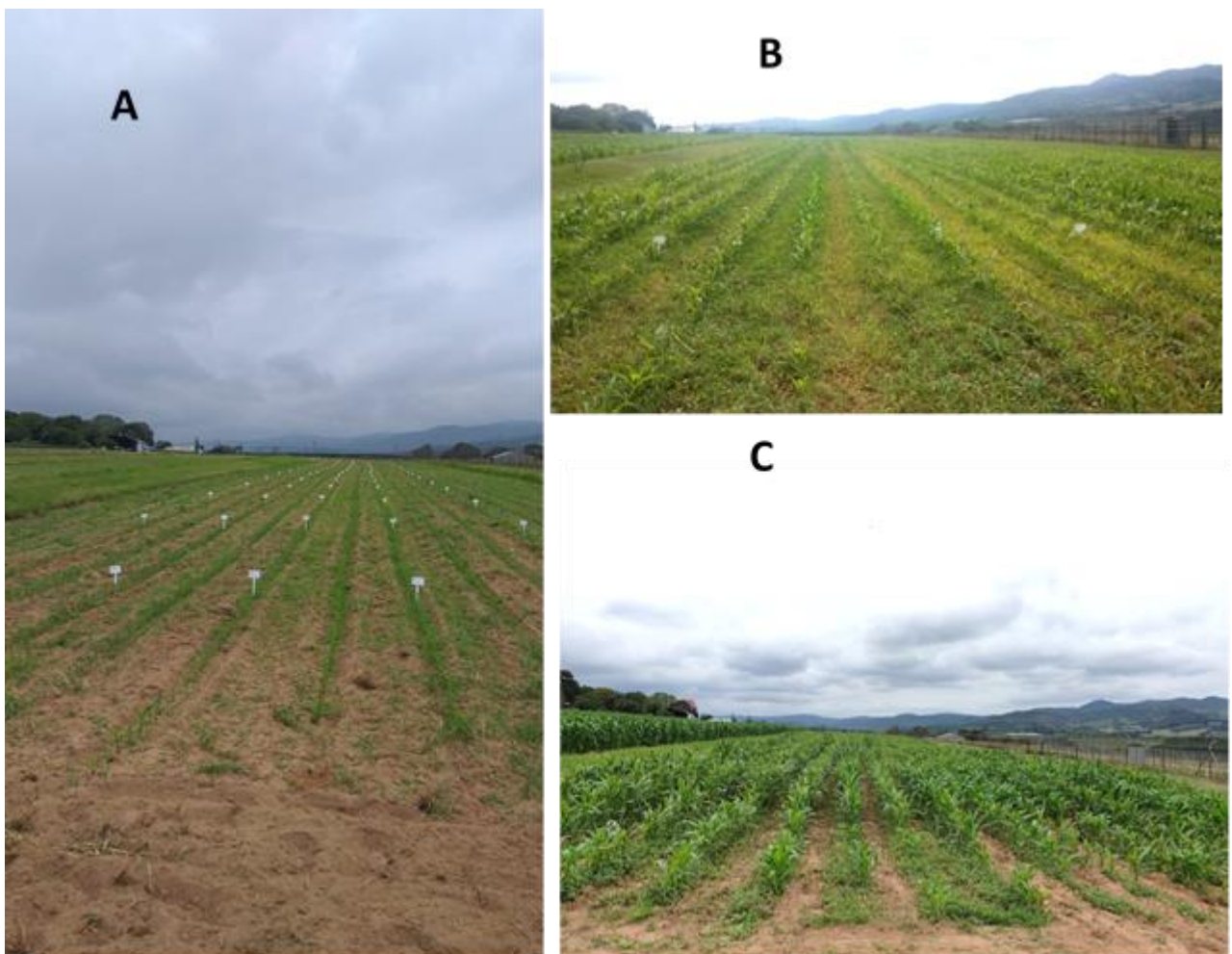


Figure 4.2. Trial 3 at Nelspruit. A) One week after seedling emergence and day of first insecticide application, B) 2 weeks after seedling emergence and after an insecticide application, and C) 5 weeks after seedling emergence.

4.2.3 Insecticide spray schedule

Treatments were divided into two spray sequences to protect plants against FAW damage for different periods of time, between the early-vegetative stages and early tassel emergence. The upper check treatment received insecticide treatments at weekly intervals from two weeks after seedling emergence to early tassel emergence. The untreated control treatment did not receive any insecticide application. The treatments (spray sequences I and II) are indicated in Table 4.1 and 4.2.

Insecticide applications were done by means of a knap-sac sprayer. Methomyl® 900 SP was applied at a rate of 200 g/ha.

Table 4.1. Insecticide application schedule for control of Fall armyworm on maize plants, from the seedling stage to tasselling, eight or nine weeks after seedling emergence. This spray schedule provided different periods of protection over different maize growing stages. The green blocks with stars indicate the time (weeks after seedling emergence) that insecticide applications were done. WAE = weeks after seeding emergence. The onset of the tassel stage in Trials 1 and 2 was at 8 WAE, respectively and 10 WAE for Trial 3.

Treatment	Crop age (weeks)								Total number of sprays	Spray Sequence
	1 WAE	2 WAE	3 WAE	4 WAE	5 WAE	6 WAE	7 WAE	8 WAE		
1	-	-	-	-	-	-	-	-	0	No spray
2	*	*	*	*	*	*	*	*	8	Upper check
3		*	*	*	*	*	*	*	7	I
4			*	*	*	*	*	*	6	I
5				*	*	*	*	*	5	I
6					*	*	*	*	4	I
7						*	*	*	3	I
8							*	*	2	I
9								*	1	I
10	*	*	*	*	*	*	*	*	7	II
11	*	*	*	*	*	*	*	*	6	II
12	*	*	*	*	*	*	*	*	5	II
13	*	*	*	*	*	*	*	*	4	II
14	*	*	*	*	*	*	*	*	3	II
15	*	*	*	*	*	*	*	*	2	II
16	*	*	*	*	*	*	*	*	1	II

Table 4.2. Crop age (weeks after seedling emergence), when insecticide applications were done in Trials 1, 2 and 3.

Crop age (weeks after seedling emergence)										
	1	2	3	4	5	6	7	8	9	10
Trial 1	√	√	√	√	√	√	√	√*	- **	- ***
Trial 2	√	√	√	√	√	√	√	√*	- **	- ***
Trial 3	√	√	√	√	√	√	√	√	-	- *

* WAE 8 = Pre-tassel, except for trial 3, ** WAE 9 = Tassel, *** WAE 10 = Flowering

4.2.4 Data collection

Plants were left until harvest to determine yield. Ears were harvested on a per plot basis and bagged. Ears were hand-threshed. Moisture analysis was conducted on the maize kernels of each plot. Grain mass was calculated at a moisture content of 11%.

4.2.5 Data analysis

Yield loss was expressed as percentage loss, relative to the yield of the upper check treatment as follows:

$$\text{yield loss (\%)} = (\text{yield upper check} - \text{yield obtained}) / \text{Yield upper check} \times 100.$$

The yield per plot and corrected percentage yield loss of each treatment were analysed by means of one-way ANOVAs, followed by Tukey's HSD tests at P = 0.05. All analyses were performed with TIBCO Statistica™ 13.3 (TIBCO Software, Inc., 2017).

4.3 Results

4.3.1 Trial 1

The mean yield of the fully protect control treatment plots (3.66 kg/plot) was 58% higher than that of the unprotected control treatment (2.13 kg/plot) (Table 4.3). The lowest yield was obtained from plots that received only a single insecticide application, at either during the seedling stage (1 WAE) or during the boot stage (8 WAE).

The mean yield of treatments receiving Sequence I sprays of which plants were protected against FAW damage for extended periods during late plant growth stages up to tassel emergence, was generally lower (2.655 kg/plot), than that of plants that were protected largely during the early growth stages (3.075 kg/plot) (Table 4.3). Mean yield loss was 28.24% for plots that received Sequence I treatments and 16.01% for Sequence II treatments. There was a marked increase in yield loss (to 20.08%) in treatments that were not protected prior to 3 WAE (protected from 3-8 WAE).

Table 4.3. Yield and yield loss (mean \pm SE) of maize plants protected against FAW damage for different periods of time, from a single week after seedling emergence to the pre-tassel stage (8 WAE) (Trial 1).

	Number of applications	Protection period (WAE)	Yield per plot (kg)	Yield loss (%)
Control treatments	0	Unprotected control	2.13 \pm 0.25 a	41.96 \pm 6.84 ab
	8	Fully protected control	3.66 \pm 0.12 c	-
Sequence I	7	2-8	3.55 \pm 0.10 c	2.96 \pm 2.62 d
	6	3-8	2.93 \pm 0.09 abc	20.08 \pm 2.49 bcd
	5	4-8	2.93 \pm 0.18 abc	20.06 \pm 4.79 bcd
	4	5-8	2.38 \pm 0.08 ab	34.89 \pm 2.27 abc
	3	6-8	1.94 \pm 0.22 a	52.68 \pm 5.96 a
	2	7-8	2.68 \pm 0.11 abc	26.71 \pm 2.93 abcd
	1	8	2.18 \pm 0.11 a	40.36 \pm 3.10 ab
			Mean	2.65
Sequence II	7	1-7	3.24 \pm 0.26 bc	11.51 \pm 7.14 cd
	6	1-6	3.28 \pm 0.24 bc	10.42 \pm 6.66 cd
	5	1-5	3.46 \pm 0.29 c	5.60 \pm 8.00 d
	4	1-4	3.26 \pm 0.27 bc	10.99 \pm 7.40 cd
	3	1-3	3.39 \pm 0.18 bc	7.42 \pm 4.86 cd
	2	1-2	2.95 \pm 0.32 abc	19.56 \pm 8.75 bcd
	1	1	1.95 \pm 0.16 a	46.61 \pm 4.41 ab
			Mean	3.07

Means within columns followed by the same letters do not differ significantly at $P < 0.05$.

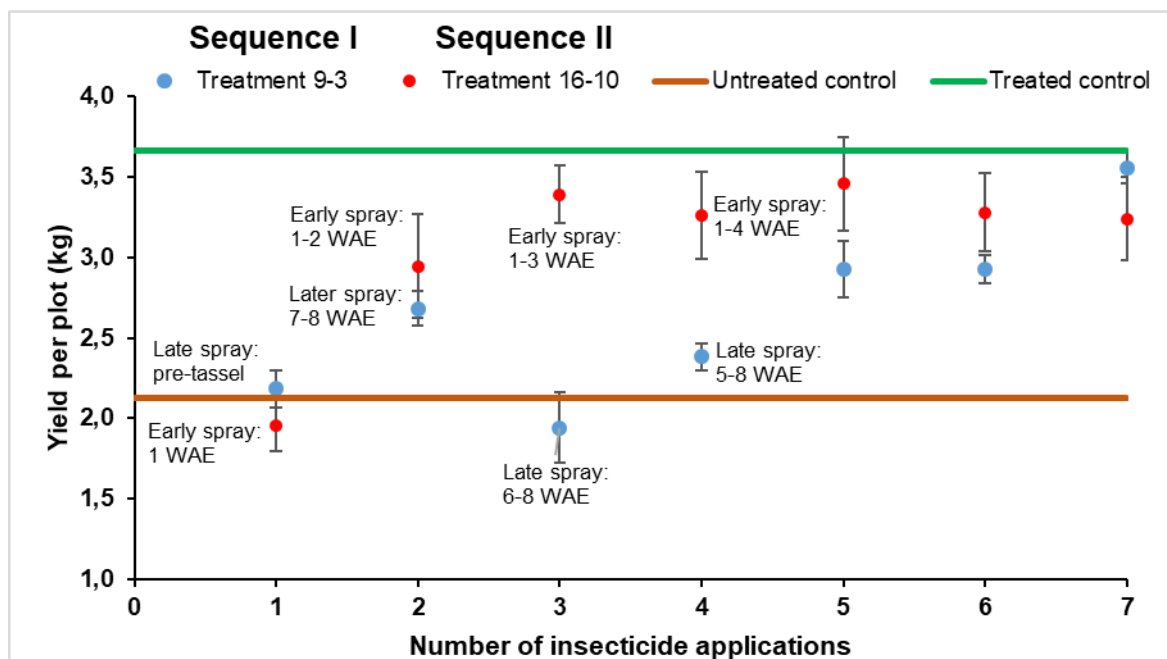


Figure 4.3. Mean yield per plot as a function of the number of insecticide sprays applied during the vegetative stages up to the pre-tassel stage of maize. Insecticide applications were done at various growth stages in a maize field with high natural *Spodoptera frugiperda* infestation levels at Malelane with first application, two weeks after seedling emergence. (Sequence I = Blue; Sequence II = red).

A single insecticide application on very young plants (1 WAE) as well as a single application when tassels started to develop did not provide any yield benefit. Similarly, protection of plants from 5 – 8 WAE only did not provide any benefit (Fig. 4.3). Two repeated applications (1 and 2 WAE) resulted in a similar yield obtained with 2 very late applications (7 and 8 WAE). Three insecticide applications that followed spraying sequence II, which provide protection during early vegetative stages (1-3 WAE), yielded the highest.

Additional insecticide applications after the early whorl period (1, 2 and 3 WAE) (Treatment 14; Table 4.1) did not provide any significant yield gain. Weekly sprays after the V5 stage (3 WAE) did not result in yield gains and yield was similar to those of treatments where 4, 5, 6 and 7 applications were made (Sequence II). There were also no differences in yield or yield gain provided by additional sprays at 5 – 8 WAE.

4.3.2 Trial 2

Yield obtained in the fully protect control treatment plots (3.44 kg/plot) was 73% higher compared to the unprotected control treatment (2.53 kg/plot) (Table 4.4). Yield production was lowest in the two plots of both Sequences I and II that received only a single insecticide application. Insecticide applications in these two sequences were done just after seedling emergence (1 WAE) and during the pre-tassel stage (8 WAE), respectively.

Implementation of control in Sequence I against FAW damage, during mid- to late-whorl vegetative stages up to tassel formation, resulted in slightly lower mean yield of treatments (2.86 kg/plot), compared to plants that received protection largely during the early vegetative stages (2.96 kg/plot) (Table 4.4). Mean yield loss was 16.90% for plots that received Sequence I treatments and 13.75% for Sequence II treatments.

Yield gains were obtained in treatments subjected to spraying Sequence II when plants were protected from a single week after emergence up to 5 WAE (2.89%) and up to 6 WAE (9.45%).

Table 4.4. Yield and yield loss (mean \pm SE) of maize plants protected against FAW damage for different periods of time, from two weeks after seedling emergence to the pre-tassel stage (Trial 2).

Protection period (WAE)		Number of applications	Yield per plot (kg)	Yield loss (%)
Control treatments	Unprotected control	0	2.53 \pm 0.1 ab	26.51 \pm 5.60 ab
	Fully protected control	8	3.44 \pm 0.31 ab	-
Sequence I	2-8	7	3.36 \pm 0.28 ab	2.24 \pm 8.10 ab
	3-8	6	3.35 \pm 0.42 ab	2.47 \pm 12.22 ab
	4-8	5	3.24 \pm 0.36 ab	5.83 \pm 10.39 ab
	5-8	4	3.02 \pm 0.15 ab	12.10 \pm 4.23 ab
	6-8	3	2.40 \pm 0.14 ab	30.05 \pm 4.18 ab
	7-8	2	2.51 \pm 0.17 ab	27.09 \pm 4.90 ab
	8	1	2.11 \pm 0.20 a	38.50 \pm 5.82 a
		Mean	2.86	16.90
Sequence II	1-7	7	3.00 \pm 0.34 ab	12.63 \pm 9.79 ab
	1-6	6	3.76 \pm 0.34 b	-9.45 \pm 9.75 b
	1-5	5	3.54 \pm 0.18 ab	-2.89 \pm 5.10 ab
	1-4	4	2.95 \pm 0.19 ab	14.09 \pm 5.43 ab
	1-3	3	2.86 \pm 0.41 ab	16.79 \pm 11.80 ab
	1-2	2	2.33 \pm 0.23 ab	32.12 \pm 6.70 a
	1	1	2.30 \pm 0.39 a	32.94 \pm 11.33 a
			Mean	2.96

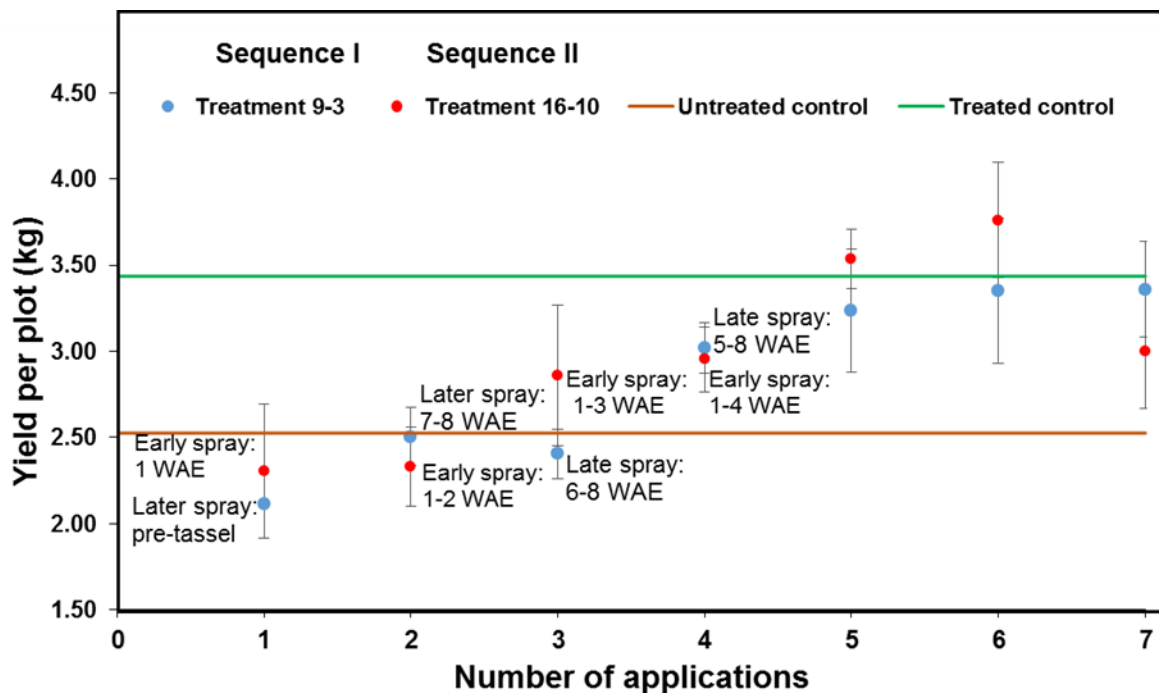


Figure 4.4. Mean yield per plot as a function of the number of insecticide sprays applied during the vegetative stages up to the pre-tassel stage of maize. Insecticide applications were done at various growth stages in a maize field with high natural *Spodoptera frugiperda* infestation levels at Malelane with first application conducted at two weeks after seedling emergence. (Sequence I = Blue; Sequence II = red).

4.3.3 Trial 3

The fully protected control treatments produced a mean yield of 3.18 kg/plot while the unprotected plot yield was 1.34 kg/plot (Table 4.5). Yield loss of the unprotected treatment plots was 57.8% in relation to the yield of the fully protected treatment. A single insecticide application in spraying Sequence II which received protection only at 1 WAE yielded the lowest (2.38 kg/plot). However, in spraying Sequence I, the lowest yield was obtained from plots that received 5 insecticide applications at 4 - 8 WAE (1.58 kg/plot).

Treatments which were subjected to the spraying schedule of Sequence I, protected against FAW damage during later vegetative stages up to tassel emergence, produced a mean yield of 2.41 kg/plot. Yield obtained subsequent to Sequence I treatments were generally lower than those from Sequence II which received protection mainly during the early vegetative development stages (2.90 kg/plot) (Table 4.5). Mean yield loss was 21.89% for plots that received Sequence I treatments and 8.91% for Sequence II treatments.

Yield gains were obtained in treatments 3 (12.50%), 10 (2.72%) and 13 (3.27%). Treatment 3 was subjected to spraying Sequence I, where plants received 7 insecticide applications from 2-8 WAE, while treatment 10 and 13 followed spraying Sequence II in which treatments received 7 (1-7 WAE) and 4 (1-4 WAE) insecticide applications, respectively.

Table 4.5. Yield and yield loss (mean \pm SE) of maize plants protected against FAW damage for different periods of time, from two weeks after seedling emergence to the pre-tassel stage (Trial 3).

Protection period (WAE)		Number of applications	Yield per plot (kg)	Yield loss (%)
Control treatments	Unprotected control	0	1.34 \pm 0.39 a	57.88 \pm 12.32 a
	Fully protected control	8	3.18 \pm 0.37 ab	-
Sequence I	2-8	7	3.58 \pm 0.42 b	-12.50 \pm 13.29 b
	3-8	6	2.44 \pm 0.34 ab	23.35 \pm 10.85 ab
	4-8	5	1.58 \pm 0.31 ab	35.01 \pm 8.96 ab
	5-8	4	2.23 \pm 0.31 ab	29.85 \pm 9.85 ab
	6-8	3	2.09 \pm 0.23 ab	34.19 \pm 7.38 ab
	7-8	2	2.29 \pm 0.18 ab	28.07 \pm 5.68 ab
	8	1	2.69 \pm 0.16 ab	15.27 \pm 5.16 ab
	Mean		2.41	21.89
Sequence II	1-7	7	3.27 \pm 0.47 b	-2.72 \pm 14.84 b
	1-6	6	2.89 \pm 0.53 ab	9.08 \pm 16.64 ab
	1-5	5	3.00 \pm 0.42 ab	5.52 \pm 13.31 ab
	1-4	4	3.28 \pm 0.42 b	-3.27 \pm 13.09 b
	1-3	3	2.54 \pm 0.23 ab	20.22 \pm 7.20 ab
	1-2	2	2.91 \pm 0.34 ab	8.34 \pm 10.65 ab
	1	1	2.38 \pm 0.53 ab	25.21 \pm 16.80 ab
	Mean		2.90	8.91

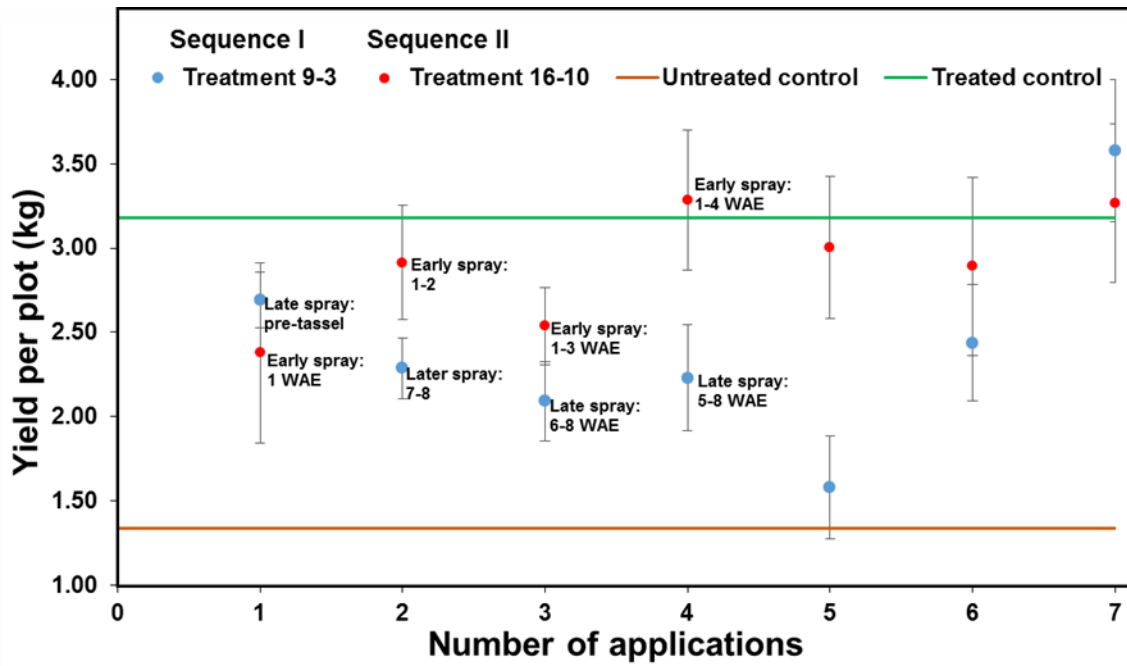


Figure 4.5. Mean yield per plot as a function of the number of insecticide sprays applied during the vegetative stages up to the pre-tassel stage of maize. Insecticide applications were done at various growth stages in a maize field with high natural *Spodoptera frugiperda* infestation levels at Nelspruit with first application being conducted at two weeks after seedling emergence. (Sequence I = Blue; Sequence II = red).



Figure 4.6. Plants in different treatment plots in Trial 3. Left: plants that received weekly insecticide applications from 1 to 8 WAE. Right: plants that received no insecticide application (control treatment).

4.4 Discussion

4.4.1 Trials 1 and 2

Under conditions of repeated infestations of the same crop and also rapid larval development, such as those observed in these trials, protection against larval damage during the early growth stages provided higher yields. Two applications (1 and 2 WAE) resulted in a similar yield obtained with two very late applications (7 and 8 WAE).

A single insecticide application on very young plants (1 WAE) as well as a single application when tassels started to emerge, did not result in any yield gain. Similarly, protection of plants from 5 – 8 WAE only, did not provide any benefit (Fig. 4.5).

The mean yields of treatments in Sequence I, of which plants were protected against FAW damage for extended periods during late plant growth stages up to tassel emergence, was generally lower than those of plants that were protected largely during the early growth stages. These results therefore generally indicated that protection of maize plants against FAW larval feeding during the early vegetative growth stages provided the largest yield gain. Additional insecticide applications after 4 WAE (for example treatment 14) did not provide any significant yield gain.

As expected, yield was higher in plots which received increased numbers of insecticide applications (Fig. 4.5, Tables 4.1 and 4.2). However, higher numbers of insecticide applications are not always correlated with higher yield, and yield losses may still occur (Dal Pogetto *et al.* 2012). These yield gains which are ascribed to increased numbers of insecticide applications are also in many cases not economically viable (Dal Pogetto *et al.* 2012). The time of insecticide application based on the growth stage of maize plants and the infestation level of FAW is more important than the number of insecticide applications (Dal Pogetto *et al.* 2012). Susceptibility of maize plants vary greatly between the different growth stages (Fenemore 1982; Buntin 1986), and it has been reported that plants are most susceptible to damage during seedling emergence and the early-whorl stages, and then again during the period of pre-tassel formation (Morrill and Greene 1974; Gross *et al.* 1982).

4.4.2 Trial 3

This trial was also conducted under environmental conditions that favoured FAW development and high pest pressure. Night temperatures at this site were comparatively low compared to those under which Trials 1 and 2 were conducted, which resulted in slower plant growth and tasselling occurring only later than 8 WAE. The lack of optimal cultivation practices which

allowed weeds to compete with maize plants, especially during the early growth stages (Figure 4.6), resulted in an extended developmental period of the maize plants at this site. Similar delays in poorly managed plantings have been reported by Van Huis (1981), Buntin (1986) and Lima *et al.* (2010). These poor cultivation practices, soil properties and presence of different weed species, interfere with important physiological functions which negatively affects plant development and recovery rate of maize plants from FAW injury. Increased yield losses due to FAW larval damage to plants that grow under stressed conditions have been reported by several authors (Van Huis 1981; Buntin 1986; Lima *et al.* 2010).

Insecticide application at very early growth stage such as the first week after seedling emergence is not necessary or economically justifiable (Brown and Mohamed 1972), since pest biology also influences this relationship. At one week after germination only egg batches or small-instar larvae at very low densities are present on leaves of the seedlings. Such low population densities, which lie below the threshold level, have no negative impact on the overall quantity or quality of the crops and its yield (Bardner and Fletcher 1974). Therefore, in maize producing regions with favourable environmental conditions which allow for continuous FAW infestations it is recommended that the first application of insecticides should be made no earlier than 2 – 3 weeks after seedling emergence (Cruz and Turpin 1983; Da Silva 1999). However, the duration and intervals of application are highly dependent on the climatic factors within each specific region (Lima *et al.* 2010; Hruska 2019). Van Huis (1981) emphasized the importance of good agricultural and cultivation practices, especially the addition of fertilizers to improve crop health and tolerance levels against FAW larvae. By simply creating more suitable growth conditions for maize plants, for example through good cultivation practices, plants may be able to tolerate higher levels of injury by larvae, which may decrease the need for frequent requirements of insecticide applications (Andrews 1988).

4.5 Conclusion

This study was conducted under conditions that favoured re-infestation by FAW during the cropping season. Seven insecticide applications on each trial resulted in yield gains of 58.1, 73.5 and 43.2% for the three respective trials. These are not economically warranted. More than three spray applications generally did not provide further yield gains. Plants that were protected more during early growth stages yield higher than plants protected during later growths stages.

4.6 References

- ALL, J.N., JAVID, A. and GUILLEBEAU, P. 1986. Control of fall armyworm with insecticides in North Georgia sweetcorn. *The Florida Entomologist* 69: 598-602.
- ANDREWS, K.L. 1988. Latin American research on *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *The Florida Entomologist* 71: 630-653.
- BARDNER, R. and FLETCHER, K.E. 1974. Insect infestations and their effects on the growth and yield of field crops: a review. *Bulletin of Entomological Research* 64: 141-160.
- BROWN, E.S. and MOHAMED, A.K.A. 1972. The relation between simulated armyworm damage and crop-loss in maize and sorghum. *The East African Agricultural Journal* 37: 237-257.
- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- CRUZ, I. and TURPIN, F.T. 1983. Yield impact of larval infestations of the fall armyworm (Lepidoptera: Noctuidae) to midwhorl growth stage of corn. *Journal of Economic Entomology* 76: 1052-1054.
- DAFF. 2017. Department of Agriculture, Forestry and Fisheries (DAFF). Guideline for registered agrochemicals to control Fall armyworm in South Africa. <https://www.daff.gov.za>. Accessed 31 October 2019.
- DAL POGETTO, M.H.F.A., PRADO, E.P., GIMENES, M.J., CHRISTOVAM, R.S., REZENDE, D.T., AGUIAR-JUNIOR, H.O., COSTA, S.I.A. and RAETANO, C.G. 2012. Corn yield with reduction of insecticidal sprayings against Fall Armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Agronomy* 11: 17-21.
- DA SILVA, M.T.B. 1999. Factors limiting the efficiency of insecticides to control *Spodoptera frugiperda* Smith in maize. *Ciência Rural* 29: 383-387.
- DAY, R., ABRAHAMS, P., BATEMAN, M., BEALE, T., CLOTTEY, V., COCK, M., COLMENAREZ, Y., CORNIANI, N., EARLY, R., GODWIN, J., GOMEZ, J., MORENO, P.G., MURPHY, S.T., OPPONG-MENSAH, B., PHIRL, N., PRATT, C., SILVESTRI, S. and WITT, A. 2017. Fall armyworm: impacts and implications for Africa. *Outlooks on Pest Management* 196-201.

- DEL ROSARIO, R. and DICLO, M. 1981. Interaccion entre diferentes densidades, control de maleza y control de gusano cogollero, *Spodoptera frugiperda*, en maiz en San Juan de Maguana, Republica Dominicana. In Memoria de la 27 Reunion Anual del PCCMCA M 28: 1-7.
- DEL ROSARIO, R., TAVAREZ, N. and MATEO, M. 1981. Incidencia del gusano cogollero *Spodoptera frugiperda* (Smithe) (sic.) en dos sistemas de labranza. In Memoria de la 27 Reunion Anual del PCCMCA M 45: 1-8.
- FENEMORE, P.G. 1982. Plant pests and their control. Wellington, NZ: Butterworths. 271p. ISBN 0-409-60087-3.
- GALT, D.L., and STANTON, B.F. 1979. Yield losses as economic weights in plant breeding decisions on tropical maize. *Cornell International Agricultural Development Mimeograph* 65: 22.
- GOERGEN, G., KUMAR, P.L., SANKUNG, S.B., TOGOLA, A. and TAMO, M. 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (JE Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in west and central Africa. *PLoS ONE*. DOI: 10.1371/journal.pone.0165632.
- GORMAN, D.P. and KANG, M.S. 1991. Preharvest aflatoxin contamination in maize: resistance and genetics. *Plant Breeding* 107: 1-10.
- GROSS JR, H.R., YOUNG, J.R. and WISEMAN, B.R. 1982. Relative susceptibility of a summer-planted dent and tropical flint corn variety to whorl stage damage by the Fall armyworm (Lepidoptera: Noctuidae). *Journal of Economic Entomology* 75: 1153-1156.
- GUTIÉRREZ-MORENO, R., MOTA-SANCHEZ, D., BLANCO, C.A., WHALON, M.E., TERÁN-SANTOFIMIO, H., RODRIGUEZ-MACIEL, J.C. and DIFONZO, C. 2018. Field-evolved resistance of the fall armyworm (Lepidoptera: Noctuidae) to synthetic insecticides in Puerto Rico and Mexico. *Journal of Economic Entomology* 112: 792-802.
- HARDKE, J.T., TEMPLE, J.H., LEONARD, B.R. and JACKSON, R.E. 2011. Laboratory toxicity and field efficacy of selected insecticides against fall armyworm (Lepidoptera: Noctuidae). *Florida Entomologist* 94: 272-278.
- HARRISON, F.P. 1984. The development of an economic injury level for low populations of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 67: 335-339.

- HARRISON, R.D., THIERFELDER, C., BAUDRON, F., CHINWADA, P., MIDEGA, C., SCHAFFNER, U and VAN DEN BERG, J. 2019. Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management* 243: 318-330.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CABI Reviews* 14: 1-11.
- HRUSKA, A.J. and GOULD, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology* 90: 611- 622.
- KUATE, A.F., HANNA R., DOUMTSOP FOTIO, A.R.P., ABANG, A.F., NANGA, S.N., NGATAT, S., TINDO, M., MASSO, C., NDEMAH, R., SUH, C. and FIABOE, K.K.M. 2019. *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Cameroon: Case study on its distribution, damage, pesticide use, genetic differentiation and host plants. PLoS ONE 14: e0215749. <https://doi.org/10.1371/journal.pone.0215749>
- LIMA, M.S., SILVA, P.S.L., OLIVEIRA, O.F., SILVA, K.M.B. and FREITAS, F.C.L. 2010. Corn yield response to weed and fall armyworm controls. *Planta Daninha, Viscosa-MG* 28: 103-111.
- MONTENEGRO, F.J. 1981. Interferencia da lagarta da folha do milho na producao do milho. Nota Previa. Fitossanidade, *Fortaleza* 5: 57-58.
- MORRILL, W.L. and GREENE, G.L. 1973. Distribution of fall armyworm larvae. Influence of biology and behavior of larvae on selection of feeding sites. *Environmental Entomology* 2: 415-418.
- MORRIL, W.L. and GREENE, G.L. 1974. Survival of fall armyworm larvae and yields of field corn after artificial infestations. *Journal of Economic Entomology* 67: 119-123.
- ORTEGA, C.A., 1987. Insect pests of maize: a guide for field identification [Internet]. Mexico: CIMMYT. Available: <https://repository.cimmyt.org/xmlui/handle/10883/700>.
- PIÑA, S. and SOLLEIRO, J.L. 2013. México, pp. 341–408 *In* Solleiro RJL, Castañón IR [eds.], Introducción al ambiente del maíz transgénico: Análisis de ocho casos en Iberoamérica, México. AgroBio México y CambioTec, México.
- PRUTER, L.S., BREWER, M.J., WEAVER, M.A., MURRY, S.C., ISAKEIT, T.S. and BERNAL, J.S. 2019. Association of insect-derived ear injury with yield and aflatoxin of maize hybrids varying in Bt transgenes. *Environmental Entomology* 48: 1401-1411.

- RWOMUSHANA, I., BATEMAN, M., BEALE, T., BESEH, P., CAMERON, K., CHILUBA, M., CLOTTEY, V., DAVIS, T., DAY, R., EARLY, R. and GODWIN, J. 2018. Fall armyworm: impacts and implications for Africa. Evidence note update. <https://www.invasive-species.org/wp-content/uploads/sites/2/2019/02/FAW-Evidence-Note-October-2018.pdf>
Date of access: 16 July 2019.
- RYDER, W. D. 1968. The fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera, Noctuidae) on maize in Cuba: its damage potential and the efficacy of different times of application of DDT in its control. *Revista Cubana de Ciencia Agricola* 2: 133-142.
- SIFUENTES, J.A. 1978. Plagas del maiz en Mexico: algunas consideraciones sobre su control. Instituto Nacional de Investigaciones Agricolas. Secretaria de Agricultura y Recursos Hidraulicos, Instituto Nacional de Investigaciones Agricolas, Mexico. Folleto de Divulgacion 58: 30pp.
- SILVA-AGUAYO, G., RODRÍGUEZ-MACIEL, J.C., LAGUNES-TEJEDA, A., LANDERAL-CÁZARES, C., ALATORRE-ROSAS, R., SHELTON, A.M. and BLANCO, C.A. 2010. Bioactivity of boldo (*Peumus boldus* Molina) (Laurales: Monimiaceae) on *Spodoptera frugiperda* (J.E. Smith) and *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae). *Southwestern Entomologist* 35: 215-231.
- SISAY, B., TEFERA, T., WAKGARI, M., AYALEW, G. and MENDESIL, E. 2019. The efficacy of selected synthetic insecticides and botanicals against fall armyworm, *Spodoptera frugiperda*, in maize. *Insects* 10: 45.
- TIBCO Software, Inc. 2017. TIBCO Statistica™ 13.3. 1984-2017.
- VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.
- WISEMAN, B.R., WASSOM, C.E. and PAINTER, R.H. 1967. An unusual feeding habit to measure differences in damage to 81 Latin-american lines of corn by the fall armyworm, *Spodoptera frugiperda* (J. E. Smith). *Agronomy Journal* 59: 279-281.
- YU, S.J. 1991. Insecticide resistance in the fall armyworm, *Spodoptera frugiperda* (JE Smith). *Pesticide Biochemistry and Physiology* 39: 84-91.

Chapter 5

Efficacy of granular insecticides for control of *Spodoptera frugiperda* in maize whorls

Abstract

Larvae of the fall armyworm (FAW), *Spodoptera frugiperda* (Lepidoptera: Noctuidae) attack maize plants from seedling emergence to after flowering, causing damage to leaves and ears. Neonate larvae migrate into plant whorls where they are protected while feeding on the soft leaf tissues. This cryptic feeding behaviour within maize whorls limits the efficacy of foliar applied insecticides. Whorl application of granular (GR) insecticide formulations was reported to be effective against FAW in South America and other lepidopteran pests such as stem borers in Africa which have similar feeding behaviour in maize, sorghum and rice. This study determined the efficacy of granular formulations and a diatomaceous earth product applied into whorls of plants, for control of FAW larvae. A laboratory and a field trial were conducted. Each trial consisted of five treatments replicated eight times, with 10 plants per replicate. The treatments in the laboratory trial were the following: water (control), spinosad SC, beta-cyfluthrin GR, carbaryl GR and a diatomaceous (DE) formulation. In the field trial, methomyl SP was used as foliar application and served as upper control treatment, instead of spinosad SC. Five-week old maize plants were inoculated with two 3rd-instar larvae each, directly into the whorls. Insecticides were applied one day after inoculation and larval survival was recorded five days later. Mass as well as the respective instars of surviving larvae were recorded. Larval corrected percentage mortality in the methomyl SP foliar application under field conditions was 80%, while it was 19.5 for carbaryl and 20.0% for beta-cyfluthrin. The mortality recorded in the DE treatment was 17.7%. In the laboratory assay, 87% mortality was achieved with beta-cyfluthrin GR after five days. Results indicate that some granular formulations of insecticides may hold promise for FAW control in small holder farming systems.

Key words: Beta-cyfluthrin; carbaryl; diatomaceous earth; methomyl; pyrethroid; spinosad

5.1 Introduction

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) occurs throughout sub-Saharan Africa and is a serious pest of maize. Yield losses result from foliar damage caused by FAW larvae to whorl tissue, leaves and ears of maize plants (Hruska and Gould 1997). Chemical control is the most commonly used and most efficient method of control against *Spodoptera* species (Christie *et al.* 2015; Dewar *et al.* 2016). In South Africa, all the insecticides registered for control of FAW are foliar applications (DAFF 2017).

FAW control by small holder farmers in Africa is constrained by poor efficacy and high costs of spray applications (Hruska 2019). The cryptic larval feeding behaviour within maize whorls affects efficacy of foliar applied insecticides (Gunewardena and Madugalla 2011). This behaviour of FAW larvae enables larvae to avoid or minimise the exposure to foliar-applied insecticides, a phenomenon which is described as behavioural resistance (Buntin 1986; Sadek 2011; Zalucki and Furlong 2017). Sub-lethal exposure levels and increased survival of exposed larvae also increases the risk of resistance evolution (Vincent *et al.* 2003; Petrovskii *et al.* 2014a, b; Gardner *et al.* 2015). Field-evolved resistance in FAW against pyrethroids, organophosphates and carbamates have been reported in Florida (USA) as long ago as 1979 (Young 1979; Pitre 1986; Yu 1991; Gunning *et al.* 1992), while Gutiérrez-Moreno *et al.* (2018) recently also reported resistance of this pest to several classes of insecticides in Mexico.

The reduced efficacy of insecticides applied against FAW is not only due to cryptic feeding behaviour of larvae (Pitre 1986), but also because insecticide applications are often done too late when larval development is at an advanced stage. Younger FAW larvae are more susceptible to insecticides which highlight the importance of insecticide applications when FAW larvae are still in the first few instars (Yu 1983). The importance of targeting insecticide application into plant whorls for control of other lepidopteran pests of maize have also been reported by Van den Berg and Van Rensburg (1993), Gunewardena and Madugalla (2011) and Adamu *et al.* (2015). Directed insecticide applications against whorl-feeding lepidopteran pests is important where plants form a dense canopy which may obstruct foliar-applied insecticides to reach FAW larvae within the maize whorls (Young 1979; Van den Berg and Van Rensburg 1996). The efficacy of control of lepidopteran pests deep inside whorls of maize plants can be improved significantly with increased downward movement of insecticides into whorls (Slabbert and Van den Berg 2009).

Application of granular (GR) or dust insecticides which have direct contact with larvae inside whorls may improve efficacy of control. Results of studies done decades ago on FAW in South America showed that granular formulations had potential to control FAW larvae (Sarmiento and Areaga 1976; Young 1979; Pitre 1986; Andrews 1980; Van Huis 1981). More recently,

Gunewardena and Madugalla (2011) and Adamu *et al.* (2015) also reported good control with granular formulations against maize stem borers, which largely occupy the same niche as FAW in plant whorls. Van den Berg and Van Rensburg (1993) reported that trichlorfon and beta-cyfluthrin granules provided effective control of stem borers. Jotwani (1983) reported effective use of dust and granular formulations of insecticides for stem borer control in maize and rice. Carbaryl has successfully been used for control of stem borers in Zimbabwe (Sylvain *et al.* 2015) and beta-cyfluthrin is registered for control of *C. partellus* which provides effective control in South Africa (Sylvain *et al.* 2015). Spinosad registered for the control of *Sitophilus* species, has a slight effect on the mating and reproductive behaviour (Velez *et al.* 2018) and has been reported to be highly effective against *Sitophilus* sp. on stored grains in Brazil (Lorini *et al.* 2006). Unfortunately, the application of pesticide granules as a technology became largely obsolete over the past decade. Insecticides most commonly applied for FAW control are foliar applications of neuromuscular toxins which influence neural transmission to muscles (Simon-Delso *et al.* 2015; Dewar *et al.* 2016).

The aim of this study was to determine the efficacy of granular and dust insecticides applied directly into the whorl of maize plants for control of FAW larvae.

5.2 Materials and methods

5.2.1 Larval rearing

Spodoptera frugiperda larvae were obtained and reared using the same method described in chapter 2 and under the same set of conditions. Seven-day old (3rd instar) larvae were used for inoculation into Petri-dishes in the laboratory assay and whorls of maize plants in the field trial.

5.2.2 Field trial

The field trial was planted at the IPM-research facility, North-West University, Potchefstroom, South Africa (26°14'31.06"S, 27°8'30.8"E). The planting consisted of 11 rows each 25 m in length at an inter-row spacing of 1.5 m. The planting date was mid-January 2019. A herbicide tolerant maize hybrid was planted to facilitate easy weed control.

The experimental layout was a randomized complete block design of five treatments in five replicates, including an untreated control (Table 5.1). Each replicate consisted of a row of 10 plants. No natural FAW infestation occurred during the experimental period.

Each maize plant was inoculated with two 3rd-instar FAW larvae. Plants were inspected to confirm the presence of larvae 24 hours after inoculation. Larvae that migrated off plants, were replaced to ensure that each plant contained two 3rd-instar larvae when application of the respective treatments was done.

The different insecticides that were used in these experiments are indicated in Table 5.1. Prior to the application of insecticides, calibration was done according to the specifications indicated on their respective labels. The amounts of carbaryl and beta-cyfluthrin granules as well as diatomaceous earth (DE) dust that had to be applied per plant were weighed on a micro-balance (Shimadzu AY220) and transferred to small vials for easy application into each maize whorl. Methomyl was applied as a foliar spray at the recommended field application rate and served as a positive control against which the efficacy of the other insecticides was compared. The control treatment was sprayed with water only.

The number of surviving larvae per plant was recorded by dissection of plant whorls, five days after insecticide application. The mass of each surviving larva was also determined to provide an indication of their growth and development when exposed to different insecticides.

Table 5.1. Active ingredients, formulations and the dosage rates of insecticides applied into maize whorls for control of *Spodoptera frugiperda*.

Active ingredient	Formulation	Dosage rate
Methomyl	SP	200 g/ha
Beta-cyfluthrin	GR	0.104 g/plant
Carbaryl	GR	0.104 g/plant
Diatomaceous earth	D	0.227 g/plant

5.2.3 Laboratory trial

The experimental design was a completely randomized one with five treatments replicated four times. Each replicate consisted of ten Petri dishes (90 mm diameter), each containing one 1st-instar larva. Treatments were applied to cover the bottom of each Petri dish. One 3rd instar larva was placed on the bottom, alongside the edge of each Petri dish. A piece of maize stem at the base of the whorl which was provided as food, was placed on the opposite end of

the Petri dish to ensure that larvae had to walk over and come into contact with the insecticide on the way to the food. The treatments are provided in Table 5.2.

This trial was conducted over five days during which larval mortality was checked each day and new food sources were also provided each day. The experiment was conducted in a climate-controlled room set at 26 ± 1 °C, $70\% \pm 5\%$ relative humidity and 14:10 L:D photoperiod.

Table 5.2. Treatments evaluated in Petri dishes to determine the efficacy of their contact action against *Spodoptera frugiperda* 3rd instar larvae.

Treatments			
Active ingredient	Formulation	Target insect on pesticide label	Reference for registration on maize
Johnson's baby powder (Control)	-	-	
Spinosad	SC	<i>Spodoptera frugiperda</i>	DAFF 2017
Beta-cyfluthrin	GR	<i>Busseola fusca</i> <i>Chilo partellus</i>	Jotwani 1983
Carbaryl	GR	<i>Busseola fusca</i> <i>Chilo partellus</i>	Sylvain <i>et al.</i> 2015
Diatomaceous earth	D	-	-

5.2.4 Data analyses

Efficacy of control in the field trial was based on % mortality which was corrected using Abbott's formula (Abbott 1925). The corrected percentage mortality data were then subjected to one-way ANOVA, followed by Tukey's HSD test. The mean mass of surviving larva per plant was determined and was subjected to one-way ANOVA, followed by unequal N HSD at $P = 0.05$. All analyses were performed with TIBCO Statistica™ 13.3 (TIBCO Software, Inc., 2017).

The proportion of insects that survived each treatment each day in the laboratory trial was calculated. These proportions were compared by means of a binomial distribution test. Bonferroni correction was used to adjust for multi-means comparisons.

5.3 Results and discussion

5.3.1 Field trial

The methomyl spray application was highly effective with mortality of 80% after 5 days. Mortality in the beta-cyfluthrin, carbaryl and diatomaceous earth treatments were similar and lower than that of the positive control (methomyl) treatment (Fig. 5.1), although these were applied directly into the whorl of maize plants where they were present within the feeding zone of larvae. In contrast to the contact action of GR and DE formulations, FAW larvae were exposed to methomyl via ingestion by feeding on sprayed leaf surfaces. Although methomyl was shown to be highly effective against FAW in South America as long ago as 1986, indications of resistance evolution by FAW to this product was reported by Pitre (1986).

The efficacy of the granular treatments applied in this experiment could have been affected by rain that occurred two days after the insecticides were applied. Precipitation can influence the efficacy of granules inside the whorls and also the behaviour of FAW larvae. Larvae are reported to remain inside the protected whorls rather than feed on the outer leaf material of the maize plants (Buntin 1986; Sadek 2011).

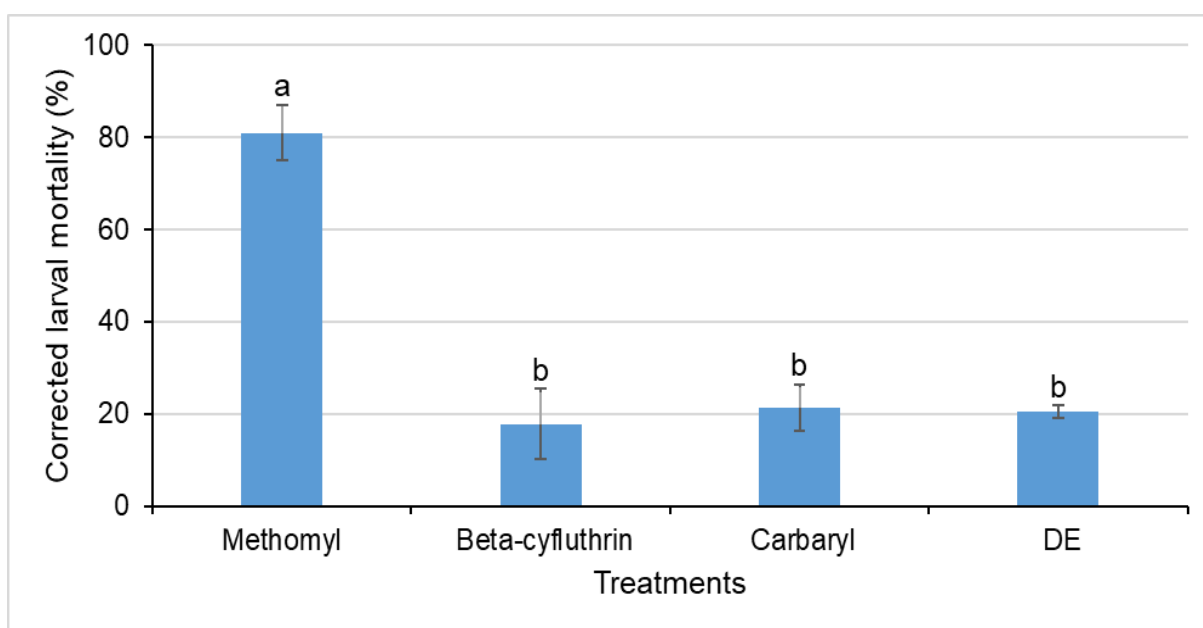


Figure 5.1. Percentage larval mortality in the field trial, five days after a foliar application of methomyl SP and granular and dust formulations of insecticides into the whorls of the maize plants. Similar letters above bars indicate that differences were not significant between treatments. DE = diatomaceous earth.

5.3.2 Laboratory trial

Larval mortality within the control group which was exposed to non-toxic Johnson's baby powder was 7% after five days (Table 5.3). Spinosad dust and beta-cyfluthrin GR were the most effective in controlling FAW larvae and resulted in 100 and 87% mortality, respectively, after 5 days. In the spinosad treatment, no live larvae were observed from day three onwards.

Table 5.3. Percentage mortality of *Spodoptera frugiperda* larvae over time, in the laboratory assay.

Treatment	Larval mortality (%)				
	Day 1	Day 2	Day 3	Day 4	Day 5
Control	5 ± 3 c	5 ± 3 d	5 ± 3 d	7 ± 5 d	7 ± 5 d
Spinosad SC	62 ± 6 a	97 ± 3 a	100 ± 0 a	100 ± 0 a	100 ± 0 a
Beta-cyfluthrin GR	57 ± 13 a	80 ± 4 b	82 ± 3 b	85 ± 3 b	87 ± 5 b
Carbaryl GR	0 ± 0 c	2 ± 2 d	2 ± 2 d	2 ± 2 d	2 ± 2 d
Diatomaceous earth	22 ± 11 b	32 ± 6c	37 ± 7 c	37 ± 7 c	40 ± 9 c

*Means within columns followed by the same letters do not differ significantly ($P < 0.05$).

Although the diatomaceous earth caused significantly lower larval mortality compared to spinosad dust and beta-cyfluthrin GR, mortalities were significantly higher compared to carbaryl GR and the control treatment. Larval mortality in the DE treatment increased over time, which indicated its slow-acting effect on *S. frugiperda* larvae.

Larval mass was not compared between treatments but there was a tendency for the mass of larvae which were exposed to beta-cyfluthrin to be lower than those exposed the other treatments. Larvae developed at varying rates and there were larvae of 4th, 5th and 6th-instar in most plant whorls after five days. There were 4th-instar larvae present in both the DE and beta-cyfluthrin GR treatments, indicating slower development of larvae exposed to these insecticides. The mass of larvae that were exposed to beta-cyfluthrin GR was, however, lower than those that were exposed to DE (Table 5.4). This study showed that spinosad dust and beta-cyfluthrin GR can provide effective control of small larvae within two days under optimal conditions with maximum exposure to these insecticides.

Spinosad dust and beta-cyfluthrin GR may be suitable for use by small holder farmers due to the low hazardous effects on humans and environmental health. However, due to the labour-

intensive application methods and lower efficacy against late-instar larvae, these products are not practical for use in large scale or commercial farming systems.

An interesting behaviour response was observed in larvae exposed to carbaryl under laboratory conditions. Individuals climbed onto the sides and lids of the Petri dishes to avoid exposure to carbaryl GR and did not feed on the whorl leaf tissue that was provided as food. This can be ascribed to overpowering chemical cues released by carbaryl which have a repellent effect on lepidopteran larvae (Zalucki and Furlong 2017). Therefore, further research needs to be conducted on the repelling effects that carbaryl have on FAW larvae and how it influences their normal behaviour. Gist and Pless (1985a, b) also reported that pyrethroids had feeding deterrent effects on FAW larvae and larval growth was adversely affected when they were exposed to sub-lethal doses of these insecticides.

Table 5.4. Instar and mean mass of surviving *Spodoptera frugiperda* larvae after five days of exposure to the respective insecticides in the laboratory assay.

Treatments	Instar	Mean larval mass (g)
Control	(5 - 6)	0,1398 ± 0.01
Spinosad	-	-
Beta-cyfluthrin	(4 - 6)	0,0800 ± 0.02
Carbaryl	(5 - 6)	0,1358 ± 0.01
DE	(4 - 6)	0,1275 ± 0.01

*Means within column followed by the same letters do not differ significantly ($P < 0.05$).

5.4 Conclusion

Granular insecticides may hold promise for FAW control in small holder farming systems where hand application of pesticides is practical. However, the efficacy of granular insecticides against FAW should be investigated further in field trials and under higher pest pressure. Development of granular formulations of more modern and safer insecticidal compounds should be investigated in the future.

5.5 References

ADAMU, R.S., USMAN, M.S. and ISAH, R. 2015. Evaluation of four insecticides foliar sprays for the management of maize stem borer, *Busseola fusca* (F.) on maize irrigated using

- furrow and basin irrigation methods at Kadawa, Kano state Nigeria. *FUTA Journal of Research in Sciences* 1: 7-14.
- ANDREWS, K.L. 1980. The whorl worm, *Spodoptera frugiperda*, in Central America and neighbouring areas. *Florida Entomologist* 63: 456-467.
- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- CHRISTIE, M.E., VAN HOUWELING, E. and ZSELECZKY, L. 2015. Mapping gendered pest management knowledge, practices, and pesticide exposure pathways in Ghana and Mali. *Agriculture and Human Values* 32: 761-775.
- DAFF. 2017. Department of Agriculture, Forestry and Fisheries (DAFF). Guideline for registered agrochemicals to control Fall armyworm in South Africa. <https://www.daff.gov.za>. Accessed 31 October 2019.
- DEWER, Y., POTTIER, M.-A., LALOUETTE, L., MARIA, A., DACHER, M., BELZUNCES, L.P., KAIRO, G., RENAULT, D., MAIBECHE, M. and SIAUSSAT, D. 2016. Behavioural and metabolic effects of sublethal doses of two insecticides, chlorpyrifos and methomyl, in the Egyptian cotton leafworm, *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae). *Environmental Science and Pollution Research* 23: 3086-3096.
- GARDNER, J., HOFFMANN, M.P. and MAZOUREK, M. 2015. Striped cucumber beetle (Coleoptera: Chrysomelidae) aggregation in response to cultivar and flowering. *Environmental Entomology* 44: 309-316.
- GIST, G.L. and PLESS, C.D. 1985a. Feeding deterrent effects of synthetic pyrethroids on the Fall Armyworm, *Spodoptera frugiperda*. *Florida Entomologist* 68: 456-461.
- GIST, G.L. and PLESS, C.D. 1985b. Effects of synthetic pyrethroids on growth and development of the Fall Armyworm, *Spodoptera frugiperda*. *Florida Entomologist* 68: 450-456.
- GUNWARDENA, K.N.C. and MADUGALLA, S.R.K. 2011. Efficacy of selected granular insecticides for the control of maize-stem borer (*Chilo partellus*) (Lepidoptera: Pyralidae). *Tropical Agricultural Research & Extension* 14: 1-4.
- GUNNING, R.V., BALFE, M.E. and EASTON, C.S. 1992. Carbamate resistance in *Helicoverpa armigera* (Hubner) (Lepidoptera: Noctuidae) in Australia. *Journal of Australian Entomology* 31: 97-103.

- GUTIÉRREZ-MORENO, R., MOTA-SANCHEZ, D., BLANCO, C.A., WHALON, M.E., TERÁN-SANTOFIMIO, H., RODRIGUEZ-MACIEL, J.C. AND DIFONZO, C. 2018. Field-evolved resistance of the fall armyworm (Lepidoptera: Noctuidae) to synthetic insecticides in Puerto Rico and Mexico. *Journal of Economic Entomology* 112: 792-802.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CABI Reviews* 14: 1-11.
- HRUSKA, A.J. and GOULD, F. 1997. Fall armyworm (Lepidoptera: Noctuidae) and *Diatraea lineolata* (Lepidoptera: Pyralidae): impact of larval population level and temporal occurrence on maize yield in Nicaragua. *Journal of Economic Entomology* 90: 611- 622.
- JOTWANI, M.G. 1983. Chemical control of cereal stem-borers. *International Journal of Tropical Insect Science* 4: 185-189.
- LORINI, I., BECKET, H. and SCHNEIDER, S. 2006. Efficacy of spinosad IGR Plus to control pests *Rhyzopertha dominica* and *Sitophilus zeamais* on stored wheat grain. *New Chemicals and Food Residues* 9: 269-273.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014a. Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks. *Physics of Life Reviews* 11: 467-525.
- PETROVSKII, S., PETROVSKAYA, N. and BEARUP, D. 2014b. Multiscale ecology of agroecosystems is an emerging research field that can provide a stronger theoretical background for the integrated pest management. Reply to comments on “Multiscale approach to pest insect monitoring: Random walks, pattern formation, synchronization, and networks”. *Physics of Life Reviews* 11: 536-539.
- PITRE, H.N. 1986. Chemical control of the Fall Armyworm (Lepidoptera: Noctuidae): an update. *Florida Entomologist* 69: 570 – 578.
- SADEK, M.M. 2011. Complementary behaviour of maternal and offspring *Spodoptera littoralis*: Oviposition site selection and larval movement together maximize performance. *Journal of Insect Behaviour* 24: 67-82.
- SALVAIN, N.M., MANYANGARIRWA, W., TUARIRA, M and KANKONDA, O.M. 2015. Effect of the Lepidoptera stem borers, *Busseola fusca* (Fuller) and *Chilo partellus* (Swinhoe) on green mealies production. *International Journal of Innovative Research & Development* 4: 366-374.

- SARMIENTO, M.J. and ARTEAGA, J.M. 1976. Efecto de la formulacion de un insecticida en el control del cogollero del maiz, *Spodoptera frugiperda*, (Lep.: Noctuidae). *Revista Peruana de Entomologia* 19: 82-84.
- SIMON-DELISO, N., AMARAL-ROGGERS, V., BELZUNCES, L.P., BONMATIN, J.M., CHAGNON, M., DOWNS, C., FURLAN, L., GIBBONS, D.W., GIORIO, C., GIROLAMI, V., GOULSON, D., KREUTZWEISER, D.P., KRUPKE, C.H., LIESS, M., LONG, E., MCFIELD, M., MINEAU, P., MITCHELL, E.A.D., MORRISSEY, C.A., NOOME, D.A., PISA, L., SETTELE, J., STARK, J.D., TAPPARO, A., VAN DYCK, H., VAN PRAAGH, J., VAN DER SLUIJS, J.P., WHITEHORN, P.R. and WIEMERS, M. 2015. Systemic insecticides (neonicotinoids and fipronil): trends, uses, mode of action and metabolites. *Environmental Science and Pollution Research* 22: 5-34.
- SLABBERT, O. and VAN DEN BERG, J. 2009. The effect of the adjuvant, Break-Thru S240, on whorl penetration and efficacy of foliar insecticide applications against *Chilo partellus*. *South African Journal of Plant and Soil* 26: 254-258.
- TIBCO SOFTWARE, INC. 2017. Statistica (data analysis software system), version 13.3. www.tibco.com.
- VAN DEN BERG, J. and VAN RENSBURG, J.B.J. 1993. Importance of persistence and synergistic effects in the chemical control of *Chilo partellus* (Lepidoptera: Pyralidae) on grain sorghum. *Applied Plant Science* 7: 5-7.
- VAN DEN BERG, J. and VAN RENSBURG, J.B.J. 1996. Comparison of various directional insecticide sprays against *Busseola fusca* (Lepidoptera: Noctuidae) and *Chilo partellus* (Lepidoptera: Pyralidae) in sorghum and maize. *South African Journal of Plants and Soil* 13: 51-54.
- VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.
- VELEZ, M., BOTINA, L.L., TURCHEN, L.M., BARBOSA, W.F. and GUEDES, R.N.C. 2018. Spinosad- and deltamethrin- induced impact on mating and reproductive output of the maize weevil *Sitophilus zeamais*. *Journal of Economic Entomology* 111: 950-958.
- VINCENT, C., HALLMAN, G., PANNETON, B. and FLEURAT-LESSARD, F. 2003. Management of agricultural insects with physical control methods. *Annual Review of Entomology* 48: 261-81.

- YOUNG, J.R. 1979. Fall armyworm: control with insecticides. *The Florida Entomologist* 62: 130-133.
- YU, S.J. 1991. Insecticide resistance in FAW *Spodoptera frugiperda* (JE Smith). *Pesticide Biochemistry and Physiology* 39: 84-91.
- YU, S.J. 1983. Age variation in insecticide susceptibility and detoxification capacity of fall armyworm (Lepidoptera: Noctuidae) larvae. *Journal of Economic Entomology* 76: 219-222.
- ZALUCKI, M.P. and FURLONG, M.J. 2017. Behaviour as a mechanism of insecticide resistance: evaluation of the evidence. *Current Opinion in Insect Science* 21: 19-25.

Chapter 6

Conclusion and recommendations

6.1 Conclusion

The response of maize plants to FAW damage is influenced by several biotic and abiotic factors. These include plant growth stage and plant health, incidence of infested plants, severity of foliar damage symptoms, duration of larval feedings and whether or not re-infestation of the crops takes place (Fenemore 1982; Gross *et al.* 1982; Harrison 1984; Buntin 1986; Ortega 1987). Environmental and climatic conditions within a given geographical region are important abiotic factors which determine the necessity of insecticide application for control of FAW larvae (Buntin 1986; Hernandez-Mendoza *et al.* 2008; Aguirre *et al.* 2016). Favourable micro-climates enable overlapping generations which further complicates pest control (Jamjanya 1987; Flanders *et al.* 2017; Kumela *et al.* 2018). Small FAW larvae (1st – 3rd –instar) are relatively easy to control and inflict low levels of damage which are difficult to detect during field scouting (Hardke *et al.* 2011; Prasanna *et al.* 2018). Therefore, once these small larvae are detected within a maize field and their population numbers or degree of damage exceeds threshold levels, chemical control needs to be implemented (Harrison 1984; Prasanna *et al.* 2018).

The cost of insecticides and its application also have a direct influence on the ETL, as can be seen with insecticide subsidies to smallholder farmers (Repetto 1985; Hruska 2019). Insecticides applied with lower costs can be applied more frequently without additional expenses, therefore lowering the ETL (Repetto 1985; Hruska 2019). This threshold is also species specific and more serious pests like the FAW also further reduce the ETL, due to more frequent insecticide application requirements at lower population densities to prevent great yield losses (Prasanna *et al.* 2018). Therefore, for effective control of the FAW, effective monitoring should be implemented throughout the growing season to keep track of any changes in their population densities that might result in economic losses (Prasanna *et al.* 2018).

In only one of the trials in this study did the degree of leaf damage during the V6/7 stage of maize plants correlate, although poorly, with yield. Yield of plants with leaf damage ratings of as high as 7, 8 and 9 did not differ from those of plants that scored damage ratings of 3. The yield loss that plants suffer is dependent on the growth stage and the level of susceptibility

expressed by the plant (Fenemore 1982; Gross *et al.* 1982; Harrison 1984; Buntin 1986; Ortega 1987). Tolerance to damage inflicted by larvae during the early vegetative stages can be ascribed to plants having sufficient time for recovery before yield-producing organs are developed and affected. Damage infliction during the boot stage, when the tassel starts to emerge, is localised to the silks and developing maize ears (Morrill and Greene 1973), which is not further presented by foliar damage.

In this study, plots with 20 - 40% infestation had lower yields compared to those that had 10% infestation if no insecticides were applied. Application of insecticides provided yield gains at all the different levels of infestation (10 – 100%) and no differences in yield was apparent at harvest. However, insecticide applications resulted in yield gains only when 30 to 60% of the plants were infested by FAW larvae of any developmental stages, compared to plots in which > 60% of the plants were already infested. Extremely high FAW infestation pressure had no effect on yield between different growth stages when no chemical control was applied. Implementation of chemical control is recommended when a 20 - 40% infestation level is recorded and larvae are still in the early instars (< 3rd instar).

This study indicated that the number of spray applications is not as important as the correct time of insecticide application (Dal Pogetto *et al.* 2012). Increased applications of insecticides resulted in higher yields. However, these high numbers of insecticide application are not necessarily economically justified (Dal Pogetto *et al.* 2012). The highest yield in field trials subjected to high levels of natural infestation, from seedling stage onwards, was generally obtained within treatments that received six or seven insecticide applications. No significant yield gains were obtained when more than three insecticide applications were made. Three insecticide applications that were made at 2, 3 and 4 WAE resulted in significantly higher yields compared to the untreated control. Generally, maize plants produced higher yields when protection was implemented during very early vegetative stages compared to plants that received their first protection only after the mid-whorl stage. Therefore, it is recommended that a maximum of three insecticide sprays should be applied during early plant growth stages, for optimum level of FAW control.

Therefore, regular and proper scouting is important to make an informed decision on whether the application of insecticides would be economically justifiable (Pedigo *et al.* 1986; Litsinger *et al.* 2006; Prasanna *et al.* 2018).

Granular insecticides provided poor control compared to methomyl sprays. Spinosad and beta-cyfluthrin provided the highest efficacy of control against FAW larvae of all granules tested in the laboratory trial. Poor penetration of granules deep into the whorl of maize plants greatly influenced the efficacy of these insecticides for control of FAW larvae. Granular

insecticides resulted in significantly lower larval mortality rates in maize fields than foliar applied methomyl sprays.

Contrary to foliar applied insecticide sprays, application of granules can be restricted to whorls of infested maize plants (Van den Berg and Nur 1998; Silvestri *et al.* 2019), which further minimizes negative impacts of insecticides on the environment. Granular insecticides are also more cost-effective and economical for use by subsistence farmers in the control of FAW larvae (Van Huis 1981; Gahukar 1993; Van den Berg and Van Rensburg 1996; Van den Berg and Nur 1998). Efficacy of granular insecticides may also be higher within small-scale farming practices, where the farmers are able to do regular scouting for the presence of egg batches or small FAW larvae (Van Huis 1981). Scouting allows early detection of FAW infestation and enables timely application of insecticides (Van Huis 1981; Adamu *et al.* 2015). In small-scale farming systems the application of granular insecticides holds many benefits (Young 1979; Gahukar 1993; Van den Berg and Van Rensburg 1996). It is easy to apply granular insecticides and there is no need for expensive spray equipment.

The focus in developing new insecticide should be enhanced to safer alternatives as provided by most granular insecticides. The efficacy of granular insecticides against FAW larvae and its direct-by-hand application into whorls of maize plants may hold promise.

6.2 Recommendations

Further studies on the correlation between damage and yield loss should be conducted in different environments to provide information that could contribute to improved decision making regarding the need for application of chemical insecticides for FAW control. Future studies should investigate the optimal time for insecticide application, according to plant growth stage, incidence of infested plants and the severity of damage symptoms.

The field trials conducted during this study should be repeated with slight adjustments to the experimental design. Additional treatments in the form of a single insecticide application, each week after seedling emergence should be included. This would provide information on the comparative susceptibility of maize plants of different growth stages to FAW damage.

Field trials can be improved by implementing another dimension in which foliar damage ratings, yield and optimal time of insecticide applications are compared in different types of cropping systems. These trials should be conducted under poor cultivation practices in order to present certain subsistence farming conditions and optimal cultivation practices that

represent commercial farmers with high input levels which include Bt maize hybrids as a positive control.

Adjustments in the experimental design of the field trial in which granular insecticide formulations were evaluated, are suggested. More information on the efficacy of spinosad will be generated by including it as an additional treatment in a similar field trial under high levels of natural FAW infestation.

Future studies should investigate if presence of carbaryl as observed inside Petri-dishes in the laboratory trial really results in behavioural changes in FAW larvae. It is recommended that both laboratory and field trials are conducted to determine the reason why FAW larvae do not move towards food (maize plant tissue) in the presence of carbaryl and whether this is also the case under field conditions inside the whorls of maize plants. These behavioural studies will show whether or not carbaryl acts as a repellent for FAW larvae.

6.3 References

- ADAMU, R.S., USMAN, M.S. and ISAH, R. 2015. Evaluation of four insecticides foliar sprays for the management of maize stem borer, *Busseola fusca* (F.) on maize irrigated using furrow and basin irrigation methods at Kadawa, Kano state Nigeria. *FUTA Journal of Research in Sciences* 1: 7-14.
- AGUIRRE, L.A., HERNANDEZ-JUAREZ, A., FLORES, M., CERNA, E., LANDEROS, J., FRIAS, G.A. and HARRIS, M.K. 2016. Evaluation of foliar damage by *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to genetically modified corn (Poales: Poaceae) in Mexico. *The Florida Entomologist* 99: 276-280.
- BUNTIN, G.D. 1986. A review of plant response to Fall armyworm, *Spodoptera frugiperda* (J.E. Smith), injury in selected field and forage crops. *The Florida Entomologist* 69: 549-559.
- DAL POGETTO, M.H.F.A., PRADO, E.P., GIMENES, M.J., CHRISTOVAM, R.S., REZENDE, D.T., AGUIAR-JUNIOR, H.O., COSTA, S.I.A. and RAETANO, C.G. 2012. Corn yield with reduction of insecticidal sprayings against Fall Armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Agronomy* 11: 17-21.
- FENEMORE, P.G. 1982. Plant pests and their control. Wellington, NZ: Butterworths. 271p. ISBN 0-409-60087-3.

- FLANDERS, K.L., BALL, D.M. and COBB, P.P. 2017. Management of FAW in pastures and hay fields. The Alabama Cooperative Extension System (Alabama A&M University and Auburn University). 1-8.
- GAHUKAR, R.T. 1993. Management of lepidopterous stem borers injurious to cereal crops in the tropics. *Agricultural Zoology Reviews* 6: 149 – 210.
- GROSS JR, H.R., YOUNG, J.R. and WISEMAN, B.R. 1982. Relative susceptibility of a summer-planted dent and tropical flint corn variety to whorl stage damage by the Fall armyworm (Lepidoptera: Noctuidae). *Journal of Economic Entomology* 75: 1153-1156.
- HARDKE, J.T., TEMPLE, J.H., LEONARD, B.R. and JACKSON, R.E. 2011. Laboratory toxicity and field efficacy of selected insecticides against fall armyworm (Lepidoptera: Noctuidae). *Florida Entomologist* 94: 272-278.
- HARRISON, F.P. 1984. The development of an economic injury level for low populations of fall armyworm (Lepidoptera: Noctuidae) in grain corn. *The Florida Entomologist* 67: 335-339.
- HERNANDEZ-MENDOZA, J.L., LOPEZ-BARBOSA, E.C., GARZA-GONZALEZ, E. and MAYEK-PEREZ, N. 2008. Spatial distribution of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize landraces grown in Colima, Mexico. *International Journal of Tropical Insect Science* 28: 126-129.
- HRUSKA, A.J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. *CABI Reviews* 14: 1-11.
- JAMJANYA, T. 1987. Consumption, utilization, biology, and economic injury level of fall armyworm, *Spodoptera frugiperda* (J.E. Smith), on selected Bermudagrasses. LSU Historical Dissertations and Theses. 4362. https://digitalcommons.lsu.edu/gradschool_disstheses/4362
- KUMELA, T., SIMIYU, J., SISAY, B., LIKHAYO, P., MENDESIL, E., GOHOLE, L. and TEFERA, T. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. *International Journal of Pest Management* 1-9.
- LITSINGER, J.A., BANDONG, J.P., CANAPI, B.L., DELA-CRUZ, C.G., PANTUA, P.C., ALVIOLA, A.L. and BATAY-AN, III E.H. 2006. Evaluation of action thresholds for chronic rice insect pests in the Philippines. III. Leafrollers. *International Journal of Pest Management* 52: 181-194.

- MORRILL, W.L. and GREENE, G.L. 1973. Distribution of fall armyworm larvae. Influence of biology and behavior of larvae on selection of feeding sites. *Environmental Entomology* 2: 415-418.
- ORTEGA, C.A., 1987. Insect pests of maize: a guide for field identification [Internet]. Mexico: CIMMYT. Available: <https://repository.cimmyt.org/xmlui/handle/10883/700>.
- PEDIGO, L.P., HUTCHINS, S.H. and HIGLEY, L.G. 1986. Economic injury levels in theory and practice. *Annual Review of Entomology* 31: 341-368.
- PRASANNA, B.M., HUESING, J.E., EDDY, R. and PESCHKE, V.M. (eds). 2018. Fall armyworm in Africa: A guide for integrated pest management, First Edition. Mexico, CDMX: CIMMYT.
- REPETTO, R. 1985. Paying the price: Pesticide subsidies in developing countries. Research Report 2. World Resources Institute, Washington. D.C. 27 pp.
- SILVESTRI, S., MACHARIA, M. and UZAYISENGA, B. 2019. Analysing the potential of plant clinics to boost crop protection in Rwanda through adoption of IPM: the case of maize and maize stem borers. *Food Security* 11: 301-315.
- VAN DEN BERG, J. and NUR, A.F. 1998. Chemical control. Chapter 26. *African Cereal Stem Borers*, CABI Book.
- VAN DEN BERG, J. and VAN RENSBURG, J.B.J. 1996. Comparison of various directional insecticide sprays against *Busseola fusca* (Lepidoptera: Noctuidae) and *Chilo partellus* (Lepidoptera: Pyralidae) in sorghum and maize. *South African Journal of Plants and Soil* 13: 51-54.
- VAN HUIS, A. 1981. Integrated pest management in the small farmer's maize crop in Nicaragua. PhD Thesis. Wageningen Agricultural University, Wageningen, The Netherlands.
- YOUNG, J.R. 1979. Fall armyworm: control with insecticides. *The Florida Entomologist* 62: 130-133.