# FINAL REPORT

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The effect of soil moisture on insecticide efficacy against the cutworm, *Agrotis segetum*

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## EXECUTIVE SUMMARY

This project commenced in October 2024 with the collection of cutworms from different areas in South Africa in order to start rearing colonies. The objectives of this study were (1) determine the effects of different soil moisture conditions on larval feeding behaviour, (2) insecticide efficacy, (3) residual effect of soil-applied insecticides, as well as (4) to assess the susceptibility of two cutworm populations to insecticides. Due to many unsuccessful attempts to establish a cutworm mass rearing colony, not all the objectives were reached. Objective 1 was successfully addressed by conducting two laboratory assays to observe the nocturnal activity of 5th-instar larvae at different soil moisture levels and the other to determine the influence of soil moisture conditions on the tunnelling behaviour of 3rd and 5th-instar larvae. The duration of larval tunnelling activity and on-surface movement was longer in dry and damp conditions, as opposed to the short and limited activity in wet conditions. Results showed that $3^{rd}$-instars did not move into the soil, as opposed the $5^{th}$-instars which occurred 20-30 mm below the soil surface. Objective 2 was partly addressed by using the information generated under Objective1. This successfully addressed the many questions that producers had regarding insecticide placement for cutworm control. Objectives 3 and 4 were not reached because of a lack of sufficient numbers of larvae to use in bioassays. This matter was discussed with personnel of the Maize Trust, just after the previous report period. In order to address the general issue of the effect of soil moisture on cutworm management and control, a review was conducted of other studies of cutworm species. This review showed that insecticide efficacy is influenced by multiple factors and not only soil moisture level.

Information generated through this study was communicated to maize produces as well as the agrochemical companies during numerous farmer's days and training events in 2025.

One MSc student which received a bursary from NWU and was trained through this project, graduated during October 2025.

## Background

Cutworm, *Agrotis segetum* (Lepidoptera: Noctuidae), is a destructive pest of maize, especially in the Highveld region of South Africa. Pesticides are commonly applied to control this pest. Over the previous three cropping seasons, poor levels of control were recorded throughout the region, leading to many reports of control failure. Although there are speculations regarding insect resistance to insecticides, the observed control failures can most likely be ascribed to other factors. Chemical control can be effective, but the efficacy of pesticide applications is influenced by larval behaviour and environmental conditions, notably soil moisture and the presence of weeds which serve as host plants of cutworm during the winter season. Furthermore, the susceptibility of cutworm to different pesticides also need be assessed. This study involves the collection of cutworms from maize fields at localities where outbreaks are reported and mass rearing of these colonies. Larvae from these colonies will used in behavioural bioassays and susceptibility screening assays. Results will benefit the maize industry by clarifying the possible underlying reasons for control failure and will lead to improved recommendations for cutworm control. If shifts in susceptibility to insecticides are detected in some pest populations, information will be conveyed to the agrochemical industry.

**The objectives of this study are to:**

1. Determine the larval feeding behaviour and survival under wet and dry soil conditions.
2. Determine the influence of different levels of soil moisture on the efficacy insecticide applications onto soil.
3. Determine the residual effect of soil-applied insecticides at different levels of soil moisture.
4. Assess the susceptibility of two cutworm populations to insecticides.

# MAIN REPORT

**OBJECTIVE 1: Determine the larval feeding behaviour and survival under wet and dry soil conditions.**

## Materials and Methods

### Collection of *Agrotis segetum* populations

An *A. segetum* population was collected from infested maize and sunflower fields at Lichtenburg (26°13'11.6"S; 26°22'05.2"E) in January during the 2024/25 planting season. The topsoil (5-10 cm) beneath injured maize and sunflower seedlings within rows were separated by hand and larvae were collected. Approximately 200 larvae were collected in order to establish a rearing colony. Larvae were placed inside transparent plastic containers aerated with plastic mesh-infused lids (380 mm x 270 mm x 140 mm) and provided weedy plants growing at the site as a temporary food source. Larvae were in transit for the minimum time feasible (< 36 hrs) and transported to the Entomology laboratory at the North-West University.

### Rearing conditions

Larvae were transferred from the temporary containers to individual clean transparent plastic containers with aerated plastic mesh-infused lids (50 mm x 50 mm x 50 mm). Stonefly *Heliothis* Premix Diet (Ward's Natural Science Establishment, LLC) was prepared with water added to the premix powder in a 3:1 ratio and provided as food to larvae. The containers were kept in a rearing room at 28 ± 1 °C, 65 ± 5% humidity and a 14L:10D photoperiod. Fresh diet was added to the rearing containers *ad libitum* and the larvae were transferred to clean containers when needed. Once pupae formed, they were removed from the rearing containers and placed in an open Petri dish (90 mm x 90 mm x 10 mm) inside an oviposition container aerated with a cotton sleeve-infused lid (420 mm x 420 mm x 200 mm). As the moths emerged, the male and female moths were free to mate. A 10% sugar solution provided in a small bottle with a cotton plug, served as an energy source for the moths. Three wax paper sheets (300 mm x 300 mm) were placed into the container for oviposition. Oviposition containers were examined daily, and the eggs which remained adhered to the wax paper were removed. Eggs that were deposited on the side and lid of the plastic containers were carefully removed with a fine paintbrush. Eggs were placed into separate transparent plastic containers aerated with steel mesh-infused lids and kept in the rearing room. Larvae that hatched from these eggs were put into transparent plastic containers aerated with plastic mesh-infused lids (50 mm x 50 mm x 50 mm). These larvae were reared to the third (L3) and $5^{th}$-instars (L5) and used in the respective experiments.

Two experiments were conducted. In the one experiment, the nocturnal behaviour of larvae was recorded by means of GoPro cameras over a 12-hour period, and in the other, the influence of different soil moisture treatments on the tunnelling depth of larvae was determined.

**Soil classification**

The soil used for this study was collected from the M-campus at the North-West University. A soil analysis conducted at Eco-Analytica laboratory (Building G23A, Ground floor, Potchefstroom Main campus) confirmed that the soil was a sandy soil. Sandy soils have a coarse texture with particles with a diameter of 0.05 to 2.0 mm, is well aerated and loose, allowing a high drainage rate (Brady & Weil, 2017).

**Determination of soil moisture conditions**

Precipitation (irrigation) is measured as a depth of water (e.g. mm of rain). Volumetric water content ($\theta_v$) is the ratio of the volume of water ($V_w$) occupied in the pore space of a volume of dry soil ($V_t$) expressed as a fraction or percentage (Formula 1) (Brady & Weil, 2017). For this reason, $\theta_v$ was used to simulate different soil moisture conditions that result from the absence or presence of rainfall or irrigation. The three soil moisture conditions used in this study were: 1) *Dry*, no additional water was added to the soil to imply un-irrigated fields or prolonged dry spells with no rainfall, 2) *Damp*, a certain amount of water was added to soil until field capacity was reached to represent an irrigated or rainfed field with optimal moisture, and 3) *Wet*, water was added until soil was drenched to simulate a saturated field directly after rainfall or excessive irrigation. For sandy soils, the standard $\theta_v$ ranges (% by volume) for each soil moisture condition are as follows: dry (2-5%), field capacity (10-20%) and saturated (25-35%) (FAO, 2006).

*Formula 1.* Calculation of volumetric water content,

$$\theta_v = \frac{V_w}{V_t} \times 100$$

Where:
$\theta_v$= Volumetric water content,
$V_w$= Volume of water added (ml),
$V_t$= Volume of soil (cm³).

Since 1 cm³ of water is 1 ml, soil volume can be directly converted to ml for the use of uniform units.

Table 1. Volumetric water content ($\theta_v$) for each treatment for each experiment.

| | Treatment | Water added (ml) | Soil volume (ml) | $\theta_v$ (%) |
|---|---|---|---|---|
| | Dry | 0 | 17 680 | 0 |
| Container | Damp | 2500 | 17 680 | 14.1 |
| | Wet | 5000 | 17 680 | 28.3 |
| | Dry | 0 | 43.75 | 0 |
| Test tube | Damp | 8 | 43.75 | 18.3 |
| | Wet | 12 | 43.75 | 27.4 |

**Experiment 1: Nocturnal behaviour of larvae**

Observations of larval behaviour under three different soil moisture treatments were made from 17:00 to 05:00. To do this, larvae were placed in containers (680 mm x 520 mm x 260 mm) filled with soil to a depth of 50 mm. At 17:00, a single L5 larva was placed into each container and left to roam around till 05:00 the following morning. GoPro cameras were mounted at the top of each container, together with an infrared light so that movement could be recorded throughout the night (Figure 1). The video material of each GoPro was reviewed to describe larval behaviour at each soil moisture treatment. Observations focused on the time it took for larvae to tunnel into the soil, larval movement above and below the soil surface, and any other responses to different soil moisture conditions.

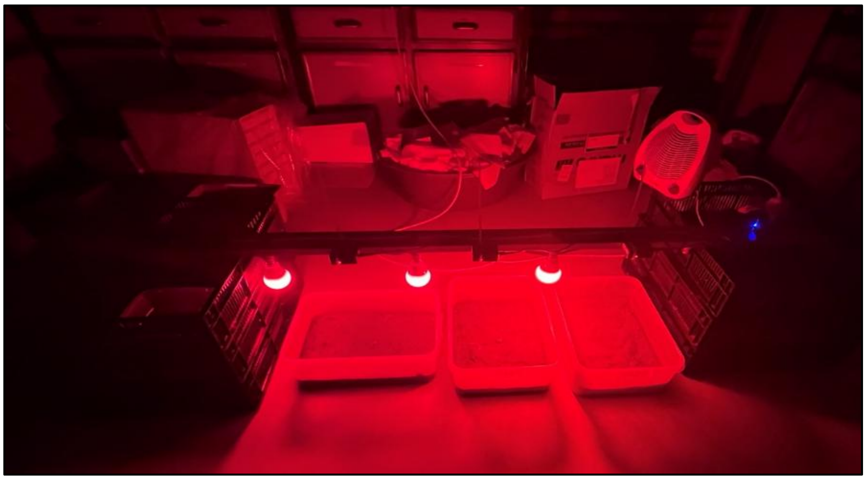

**Figure 1.** Experimental setup for observation of 5$^{th}$-instar larval behaviour at three soil moisture conditions.

**Experiment 2: The influence of different soil moisture treatments on the tunnelling depth of larvae**

Two laboratory assays were conducted to determine the influence of soil moisture on the tunnelling depth of cutworm larvae. In the one assay, L3 larvae were used and in the other, L5. The three soil moisture conditions listed in Table 1 were used as the different treatments and each treatment was replicated 54 times.

The study was conducted in glass test tubes to facilitate easy observation of larval depth. Test tubes (25 mm x 25 mm x 200 mm), were filled with soil to a depth of 160 mm. For each treatment, water was added to achieve the desired $\theta_v$ within the top 50 mm of the soil (Table 1). A single L3 or L5 larva was inoculated per test tube at 17:00 after which the tubes were covered with a mesh material to prevent the escape. Test tubes were placed in a dark room for 24 hours. The depth (mm) that larvae had tunneled into the soil was measured after 24 hours.


**Figure 2.** Experimental setup with test tubes to observe tunnelling behaviour of cutworms at three soil moisture conditions.

### Data analysis

Observations on the time that larvae spent burrowing in soil or walking on the soil surface were summarized in Excel. Turkey HSD tests were used to indicate significant differences between the depths that larvae moved into the soils of the different treatments. All statistical analyses were performed with TIBCO® Statistica™ software version 14.0.1.25 (TIBCO, 2020).

## Results

### Experiment 1: Nocturnal behaviour of larvae

The behaviour of larvae varied in the three soil moisture conditions (Figure 3). In dry soil, the larva was highly active throughout the night. The larvae emerged and entered the soil repeatedly, and at different entry points within the container. For a duration of 122 minutes, the larvae extensively moved around in the container, from corner to corner, in a seeking manner. Tunnelling and on-surface movement continued intermittently.

In the container with damp soil, the larvae struggled for 39 minutes before it successfully tunneled into the ground. For a total period of 138 minutes the larvae emerged intermittently to move along the edges of the container.

Under wet soil conditions, the larva took six minutes to tunnel into the soil. The larva remained below the soil for the duration of the observation period.

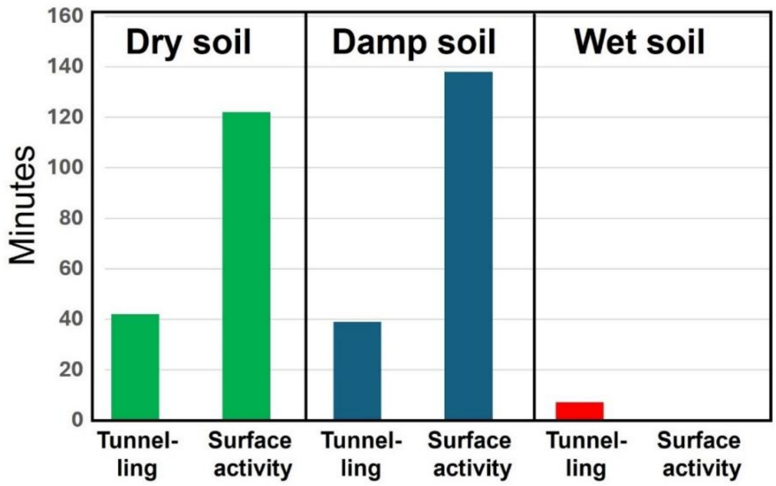


**Figure 3.** Time (minutes) spent by *Agrotis segetum* larvae tunnelling within or crawling on top of the surface of dry, damp or wet soil.

**Experiment 2: The influence of different soil moisture treatments on the tunnelling depth of larvae**

L3-larvae showed minimal tunnelling activity at all three soil moisture conditions. In dry soil, no L3 larvae tunneled below the soil surface (Figure 4A). In the damp and wet soil, the mean depths at which larvae occurred below soil surface were 15 mm and 16 mm, respectively. Larvae tunneled significantly ($p = 0.040$) deeper into damp and wet soil than dry soil (Figure 4A). This significant difference is, however, ascribed to the fact that none of the L3 larvae tunneled into the dry soil. In the damp soil, only six L3 larvae tunneled into the soil, with depths ranging from 10 to 20 mm. In the wet soil treatment, only six L3 larvae tunneled into the soil, with some going as deep as 30 mm.

In the dry soil, most L5 larvae (90.7%) tunneled into the soil to a mean depth of 29.4 mm. In the damp and wet soils, 96.2 and 90.7% of larvae tunneled into the soil. The mean depths at which L5-larvae occurred in damp and wet soils were 22.8 and 24.5 mm respectively. Some larvae in the wet soil occurred up to a depth of 60 mm.

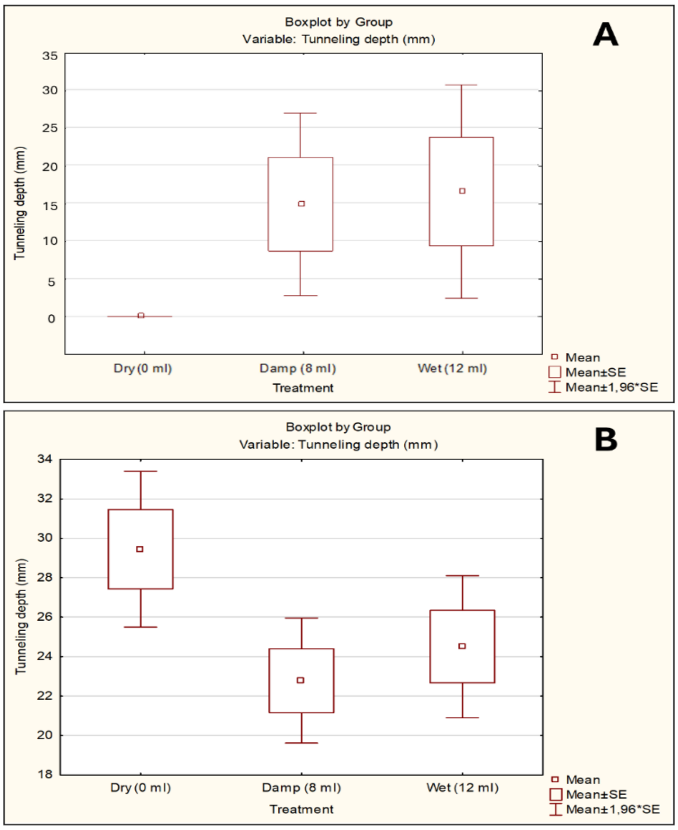


**Figure 4.** Mean distance (mm) of third-instar (A) and fifth-instar (B) *Agrotis segetum* larvae below the surface of dry, damp or wet soil.

## Discussion

This study on larval behaviour showed that L5 larvae spent much less time above the soil surface when soil is wet, than under dry or damp conditions. Larvae under damp and dry conditions spent between 122 and 138 minutes walking the soil surface. This study shows for the first time, the surface activity of *A. segetum* larvae under different soil moisture conditions in South Africa. In Canada, Jacobson and Blakeley (1957) reported that larval movement and feeding of *A. orthogonia* was influenced by the soil moisture gradient, with these activities usually occurring at the interface between dry and moist soil. When there is a gradient from dry to moist conditions from the surface downward, the larvae move to that level in the soil that provides the preferred environmental conditions. Other studies in Europe and the United States have reported that burrows result from the tunnelling behaviour of larvae and serves as a site of refuge from which the larvae emerge at night and search the surface for food (Blair, 1975; Bowden *et al*., 1983). The intermittent tunnelling and on-surface larval activity in the damp and dry treatments suggests that larvae were searching for food. Although this study did not include available food resources, other studies in South Africa, India and the United States have reported that a single larva can damage several seedlings when it emerges from the soil at night (Du Plessis, 2000; Chandel *et al*., 2022) and in many cases, a single seedling is severed and partially or entirely pulled beneath the surface for consumption (Manis, 1936, Drinkwater, 2017).

This study showed that the tunnelling behaviour of L3 and L5 *A. segetum* larvae differ under different soil moisture conditions. While L3 larvae showed limited tunnelling into the soil, most of the L5 larvae tunnelled to a depth of < 22 mm into the soil, irrespective of soil moisture level.

This difference in behaviour between the L3 and L5 instar larvae is confirmed by other studies in other parts of the world that revealed characteristic changes in behaviour of *A. segetum* larvae during its development and the influence of soil moisture. According to Blair (1975), 1$^{st}$ to 3$^{rd}$ instar *A. segetum* larvae is photopositive and occur above-ground but start to exhibit a negative response to sunlight between the fourth and fifth day in the 3$^{rd}$ instar. The physiological mechanism for the change in phototaxis is not known (Blair, 1975). In Europe, Esbjerg (1989) reported that L3 larvae are highly dependent on soil moisture, which confirms the fact that L3 larvae in this study evaded tunnelling into the soil, especially the damp and wet treatments. From the L3 onwards, *A. segetum* larvae start to hide in the soil rather than above the soil surface (Garnis & Dabrowski, 2008; Jakubowska & Bocianowski, 2013; Drinkwater, 2017). The few L3 larvae that tunneled into the soil in this study must have just completed their moulting and was between the 4$^{th}$ and 5$^{th}$ day of the 3$^{rd}$ instar and changed to photonegative behaviour.

**OBJECTIVE 2.** Determine the influence of different levels of soil moisture on the efficacy insecticide applications onto soil.

Based on the above-mentioned information generated on larval distribution in the soil profile, this objective was partly successful. The bioassays on larval behaviour in dry and wet soil showed that their vertical movement is not strongly influenced by soil moisture (Fig. 5).

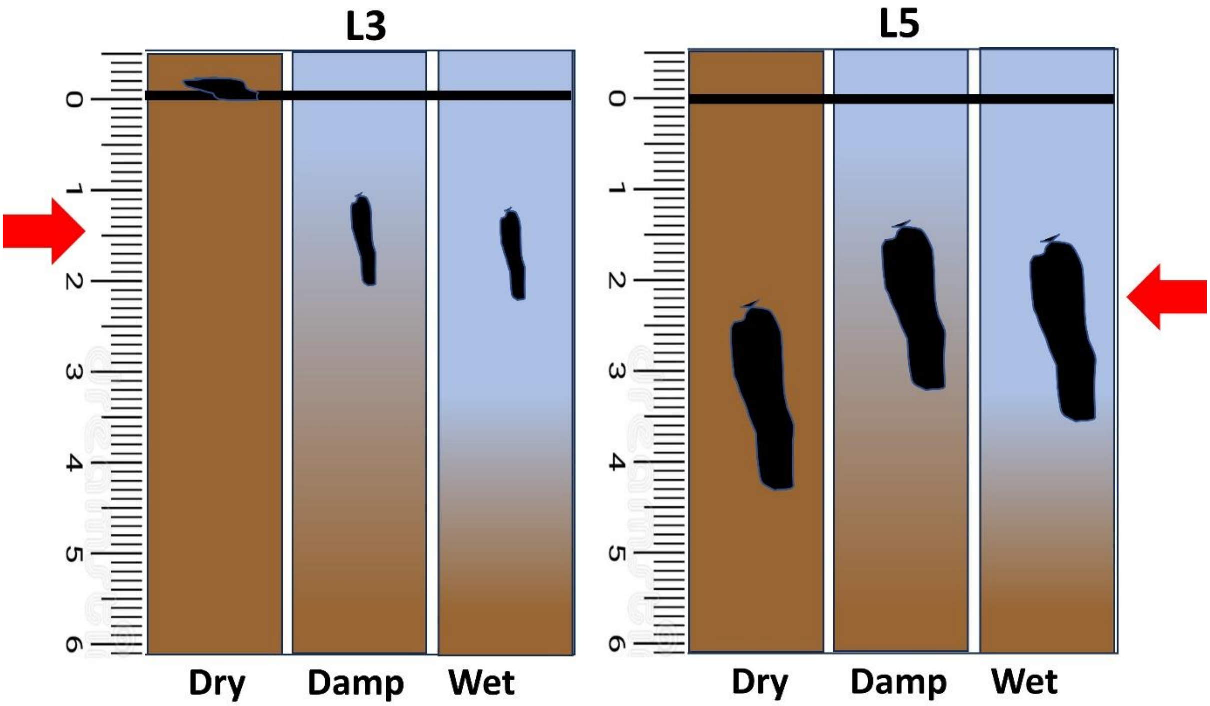


**Figure 5.** Mean depth (mm) of L3 and L5 cutworm larvae below the surface of dry, damp or wet soil.

For this reason, producers do not have to work insecticides deep into the soil because: 1) larvae move around on top of the soil at night, and 2) larvae, irrespective of size (L1 & L3) and soil moisture level, do not penetrate deeper than 3 cm into the soil.

The possible placements of soil applied insecticides, nematicides and fungicides within a soil profile is illustrated in figure 6. This information was shared with producers at many farmer's days as well as with the agrochemical industry during training events in 2025. The message that was conveyed was that soil moisture levels did not significantly affect the distance that cutworm larvae moved into the soil, and insecticides applied for cutworm control do not have to be worked into soils. Insecticides should preferably be applied on top of the soil surface, where cutworm larvae move around at night.

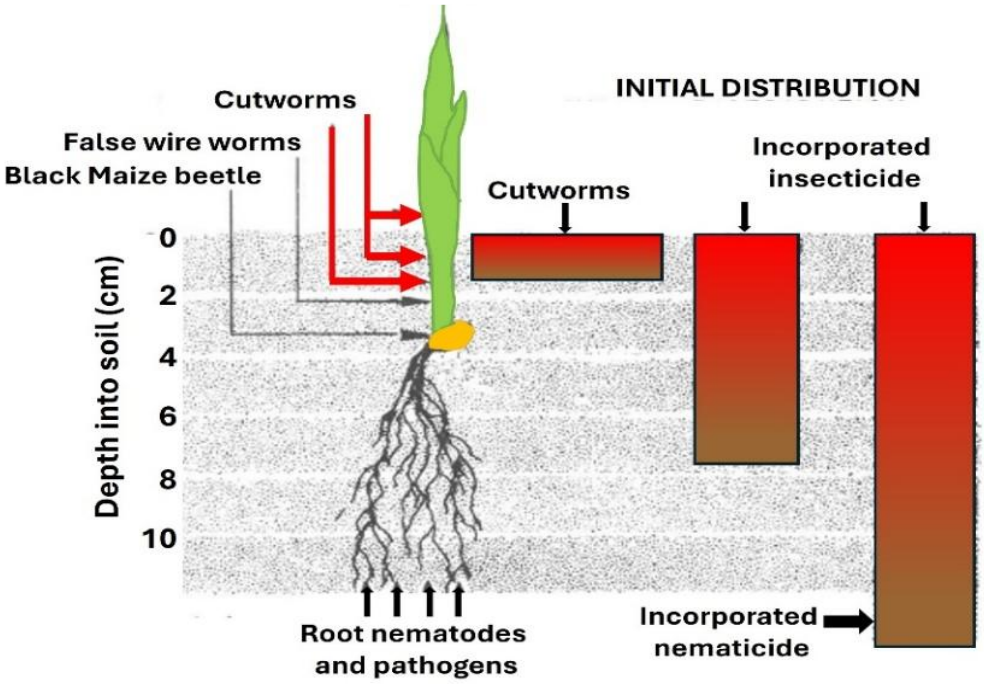


**Figure 6.** Distribution of target pests and pesticides in soil.

The other component of this objective, i.e., was not reached because of a lack of sufficient numbers of larvae to use in bioassays. This was not due to a lack of effort but due to the extremely high and unexpected levels of parasitism and disease infection of cutworm larvae that were collected from the field. Parasitism ranged between 41.6 to 92.1% for the different localities where larvae were collected from in previous report periods.

The last activity conducted during this project was collection of a cutworm population at Ottosdal (**15 September 2025**). Due to parasitism and entomopathogenic infections, only 6 of the 54 larvae that were collected, survived until the pupal stage.

However, a review was done of the literature on the effect of soil moisture on the behaviour and control of *A. segetum* as well as other cutworm species. (APPENDIX A).

**OBJECTIVE 3.** Determine the residual effect of soil-applied insecticides at different levels of soil moisture.

This objective was not reached because of a lack of sufficient numbers of larvae to use in bioassays. This matter was discussed with personnel of the Maize Trust, just after the previous report period.

**OBJECTIVE 4.** Assess the susceptibility of two cutworm populations to insecticides.

This objective was not reached because of a lack of sufficient numbers of larvae to use in bioassays. This matter was discussed with personnel of the Maize Trust, just after the previous report period.

## Conclusions

The component of the research conducted under **Objective 1** showed that L5 larvae spent more time above the soil surface when soil is dry or damp, than under wet conditions. Results further showed that L3-larvae do not enter the soil at all under dry conditions, and that the distance at which they occur underneath the soils surface is not influenced by soil moisture condition (Mean distance = 15 mm). L5-larvae moved deeper not the soil when it was dry, compared to damp and wet conditions but there were no significant differences between treatments, which indicates that cutworm larvae occur largely within the upper 30 mm of soil.

**Objective 2** was partly addressed by using the information generated under Objective1. This successfully addressed the many questions that producers had regarding insecticide placement for cutworm control.

**Objectives 3 and 4** were not reached because of a lack of sufficient numbers of larvae to use in bioassays.  This matter was discussed with personnel of the Maize Trust, just after the previous report period.

# APPENDIX 1

## Review of literature on the effect of soil moisture on cutworm behaviour and control

Chemical control of cutworms is complicated by the behaviour and biology of larvae, as well as environmental factors such as temperature, fluctuating soil moisture levels, the presence of weeds during winter, and varying conditions across fields (Drinkwater *et al.*, 1980; Jakubowska & Walczak, 2008).

Variations in temperature, precipitation, and soil moisture can have both direct and indirect effects on insect pests (Kocsis & Hufnagel, 2011; Skendžić *et al.*, 2021; Saha & Dutta, 2025). Directly, the reproduction, development, survival and distribution of insect pests are affected, whereas indirectly, their interaction within the environment is affected (Woiwod 1997; Nyamukondiwa *et al.*, 2022). In other studies, the direct and indirect effects of soil moisture on the ecology and behaviour of cutworm species have been reported. In Canada, the **dark-sided cutworm**, *Euxoa messoria* (Harris) (Lepidoptera: Noctuidae) is attracted to dry soil and tunnels early in the 3$^{rd}$ instar, whereas the **black cutworm**, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae), does not tunnel until later in the 3$^{rd}$ instar and is attracted to moist soil (Harris & Svec, 1968a, 1968b, 1968c; Harris, 1972). However, the **variegated cutworm**, *Peridroma saucia* (Hübner) (Lepidoptera: Noctuidae) also prefers moist soil and only tunnels late in the 5$^{th}$ instar. In Canada, Jacobson and Blakeley (1957) reported that larval movement and feeding of the **pale western cutworm**, *Agrotis orthogonia* (Morrison) (Lepidoptera: Phalaenidae), occurred in the interface between dry and moist soil. Furthermore, larvae can absorb moisture from the soil and the plants on which they feed.

In the United States, Manis (1936) reported that *A. ipsilon* moths refrain from depositing their eggs in moist soil and that dry soil increases the duration of the larval stages. The optimum soil moisture for successful larval development was between 25 to 30%, however, prepupae and pupae were able to develop successfully in soil with a moisture content of up to 58%.

In Europe, the growth and survival of larvae are strongly influenced by the complex interactions between soil moisture and temperature. While high soil moisture has a cooling effect on soil temperature, high temperature, on the other hand, dries out the upper soil surface (Esbjerg & Sigsgaard, 2014; Esbjerg & Sigsgaard, 2019). *Agrotis segetum* moths prefer to oviposit on dry rather than moist soil (Esbjerg & Lauritzen, 2010). High mortality of 1$^{st}$ and 2$^{nd}$-instar *A. segetum* larvae is experienced in moist soil and at low soil temperatures (Esbjerg *et al.*, 1986; Esbjerg, 1989; Esbjerg & Vidal, 2003). Larvae in the 3$^{rd}$-instar are also dependent on soil moisture, however, from the 4$^{th}$ instar onwards, *A. segetum* larval tolerance to cold and moist conditions increase (Esbjerg, 1989; Esbjerg & Sigsgaard, 2019). The depth of pupation in the soil is also influenced by soil type and moisture levels (Blair, 1975). Pupation takes place within the top 30-50 mm of the soil and the higher the moisture content, the shallower the depth at which pupation occurs (Blair, 1975). In South Africa, during very wet conditions, *A. segetum* larvae come to the soil surface and may also exhibit climbing behaviour on plant material (Drinkwater, 1980).

Abiotic conditions do not only influence pest pressure and damage potential but also insecticide efficacy (Saha & Dutta, 2025). The efficacy of insecticides registered for the control of cutworms in other countries was reported to be influenced by soil moisture, along with other factors such as soil type, larval behaviour, method of application and formulation (Harris & Svec 1968a, 1968b, 1968c; Harris, 1972). Furthermore, insecticides efficacy against cutworms may also be influenced by the distribution of the active ingredients in soil profile, adsorption or rapid break down due to sunlight (Leistra & Green, 1990), and the impracticality of applying contact insecticides (Harris & Svec 1968a, 1968b, 1968c; Harris and Svec, 1970). Although the requirements for the effectiveness of insecticides differ, many principles remain the same (Leistra & Green, 1990). Pyrethroids have become a predominant class of insecticide used against insect pests, especially lepidopteran larvae, as a substitute for highly toxic organophosphorous insecticides (Gajendiran & Abraham, 2018). Pyrethroids are particularly effective due to their strong lipophilicity and low water solubility, which allows rapid adsorption to soil particles (Leistra & Green, 1990). These properties limit the leaching in soil, which is ideal for cutworm control, since they spend most of their life cycle just below the soil surface. Currently used pyrethroids are oil-based emulsifiable concentration formulations that retain pyrethroids in its liquid form and enhance their persistence in soils (Saha & Dutta, 2025). Insecticide labels from agrochemical companies provide clear instructions regarding the environmental conditions under which these products should be applied to ensure optimal efficacy (Agri-Intel, 2023, IRAC, 2024). For instance, the general label recommendations for *A. segetum* are that soil must be prepared, and the top 30 mm must be moist at the time of insecticide application.

Esbjerg (1989) further reported that *A. segetum* larvae's ability to tolerate moist conditions increases when they reach the 4$^{th}$, 5$^{th}$ and 6$^{th}$ instars, which was confirmed by the observation that the L5 larvae in this study tunnelled into soil, irrespective of soil moisture level. Other studies have reported that cutworm species habits and their reaction to soil moisture may vary. In Canada, Harris and Svec (1968c) reported on the tunnelling (burrowing) behaviour of three cutworm species, i.e., black cutworm, *Agrotis ipsilon* (Hüfnagel), dark-sided cutworm, *Euxoa messoria* (Harris) (Lepidoptera: Noctuidae) and variegated cutworm, *Peridroma saucia* (Hübner) (Lepidoptera: Noctuidae). *Euxoa messoria* started to tunnel at the beginning of L3, *A. ipsilon* in the latter part of L3, whereas *P. saucia* only started to tunnel in L5. Furthermore, *E. messoria* prefers dry soil, but do tunnel in moist soil, whereas *P. saucia* and *A. ipsilon* prefer moist soil. The latter species will only tunnel into dry soils after spending an extensive time on the soil surface.

Although an experiment to determine the influence of soil moisture on the efficacy of soil-applied insecticides to control *A. segetum* could not be completed, other studies have reported valuable information that suggests insecticide efficacy against cutworms are influenced by numerous factors. No recent studies on this topic were found. In this study, the larval behaviour of *A. segetum* changed according to soil moisture and larval stage. Similarly, Harris and Svec (1968a, 1968b) reported that larval tolerance of *A. ipsilon* and *E. messoria* to insecticides increase with larval stage, which makes control efforts against larger larvae (L4-L6) less effective. For example, a concentration of 0.1% chlorpyriphos caused 100% mortality of 1$^{st}$-instar *A. ipsilon*, but 0% mortality of 5$^{th}$ and 6$^{th}$-instar larvae. This high tolerance of larger larvae to contact insecticides was ascribed to poor penetration of the integument by the insecticide. Harris and Svec (1968a) therefore suggested that insecticide applications should be made early in the season to target small larvae (L1-L3), regardless of planting time.

The efficacy of insecticides is also influenced by the cutworm species. According to Harris and Svec (1968c), varying insecticide rates were required to control *P. saucia*, *A. ipsilon* and *E. messoria* because of larval behaviour differences. Each species burrows at different instars, i.e., *E. messoria* early in L3, *A. ipsilon* later in L3 and *P. saucia* only in L5. Furthermore, each species has its own soil moisture preference with *E. messoria* preferring dry soil, whereas *A. ipsilon* and *P. saucia* prefer moist soil. For this reason, Harris and Svec (1968c) suggested that an insecticide that is effective as a contact insecticide to one species, may be less effective to another species as a soil insecticide.

Insecticide efficacy was found to be influenced by soil moisture, soil type and organic content. In studies of *A. ipsilon* and *E. messoria*, Harris and Svec (1968a, 1968b) reported that in sandy soils, which dry quickly, chlorpyriphos were more effective when incorporated into the soil whereas in the sandy loam and muck soils, which retain moisture better, surface applications of chlorpyriphos were four times more effective than when the insecticide was incorporated into the soil.

Another limiting factor is adsorption. The physiochemical properties of insecticides influence their effectiveness as a soil treatment (Harris, 1972). Although an insecticide may be highly toxic, its toxicity as a soil insecticide may differ due to differing levels of adsorption by the soil. For example, methomyl was the most toxic direct contact insecticide, but the least effective in the soil. Other highly effective (and banned) contact insecticides, i.e., parathion (organophosphate) and DDT (organochlorine), are strongly adsorbed by the soil, and therefore less active as a soil treatment, however chlorpyriphos, aldrin (organochlorine) and trichloronate (organophosphate) were less adsorbed by the soil, thus effective as soil insecticides.

The method of insecticide application and soil moisture is another influencing factor. According to Harris and Svec (1970), most insecticides are adsorbed and become inactivated in dry soil while they are desorbed and activated in moist soil. To confirm, Harris and Svec (1970) tested the toxicity of six emulsifiable concentrate (EC) formulations against L4 and L5 *E. messoria* larvae using field-moist or airdry conditions for surface and incorporated applications. Results showed that insecticides were less effective in dry soil, especially when applied onto the surface. Soil-surface applications were complicated by the deactivation of insecticides in dry soil and the rapid degradation of short-residual compounds on the surface. Harris and Svec (1968a) also reported that chlorpyriphos (EC) was more effective when incorporated into the soil than when applied onto the soil surface, since surface applications became inactive when the soil dried. The incorporation of the EC into the soil helped to maintain consistent soil moisture levels, which kept the insecticide active. It was concluded that to obtain cutworm control, insecticides had to be incorporated into the top 5 cm of the soil and that applications must be made while the soil is moist to extend the activity of the insecticide. Leistra and Green (1990) also reported that the distribution of insecticides should be matched to the spatial pattern of the insect pest. Surface applications are exposed to sunlight that might cause photochemical transformation and rapid activity loss. In the case of cutworms, which occur in the soil at shallow depths and attack crop plants below the soil surface, Leistra and Green (1990) suggested that effective control may be achieved by the incorporation of insecticides into the soil. Insecticide labels from agrochemical companies in South Africa provide instructions regarding the environmental conditions under which insecticides should be applied to ensure optimal efficacy (Agri-Intel, 2024). For *A. segetum*, labels indicate that soils must be prepared, and the top 30 mm must be moist at the time of insecticide application.

Formulation is also an influencing factor. According to Harris and Svec (1968c), dust formulations are most effective when emergency control is needed, whereas emulsifiable concentrations are the most consistent type of formulation whether applied as a pre-planting treatment onto the soil surface or incorporated into the soil. No dust formulations of insecticides aimed at cutworm control are however registered in South Africa.

Leistra and Green (1990) listed the factors that influence the efficacy of soil-applied insecticides as follows: properties of the insecticide, application method, properties of the soil, climatic conditions and the behaviour of the pest. From this review, it is clear that cutworm control is challenged by more than one factor and that insecticide resistance may not be the reason for poor cutworm control as experienced over the past four planting seasons in South Africa.

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